Frequency Combs for the Calibration of Astronomical Spectrographs

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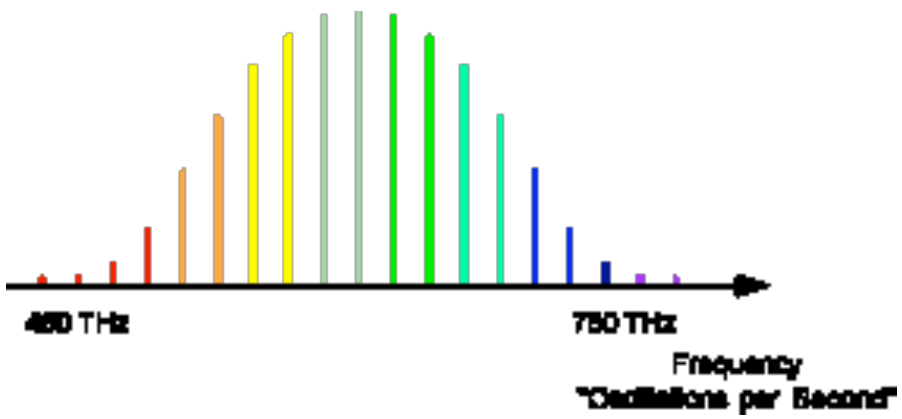
Garching, Germany

Fermilab
April 18th 2012

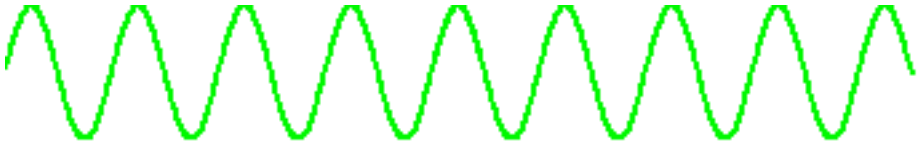
Calibration with Frequency Combs

1. **What are „Frequency Combs“?**
2. Spectrograph Calibration with Combs
3. Test at HARPS



The Comb Idea

Counting oscillations of light waves!

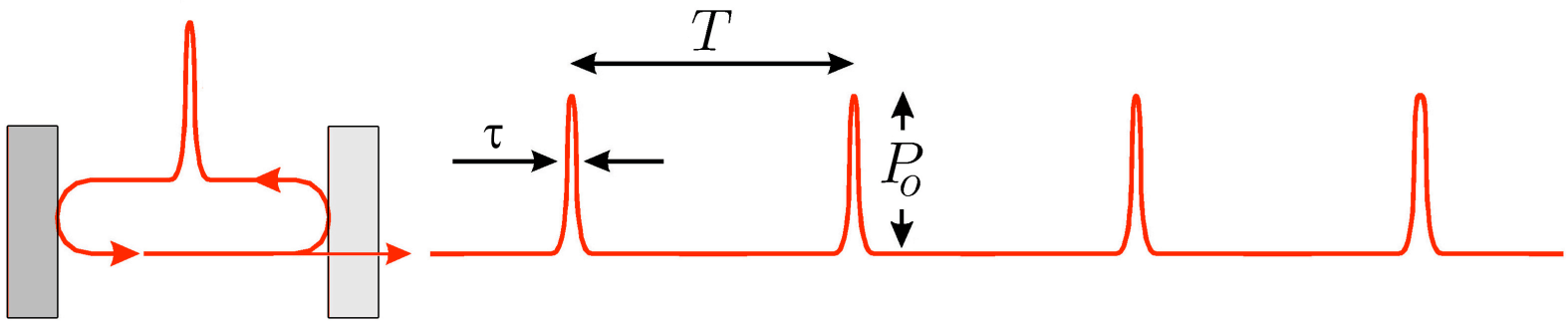


532 nm or 560 THz

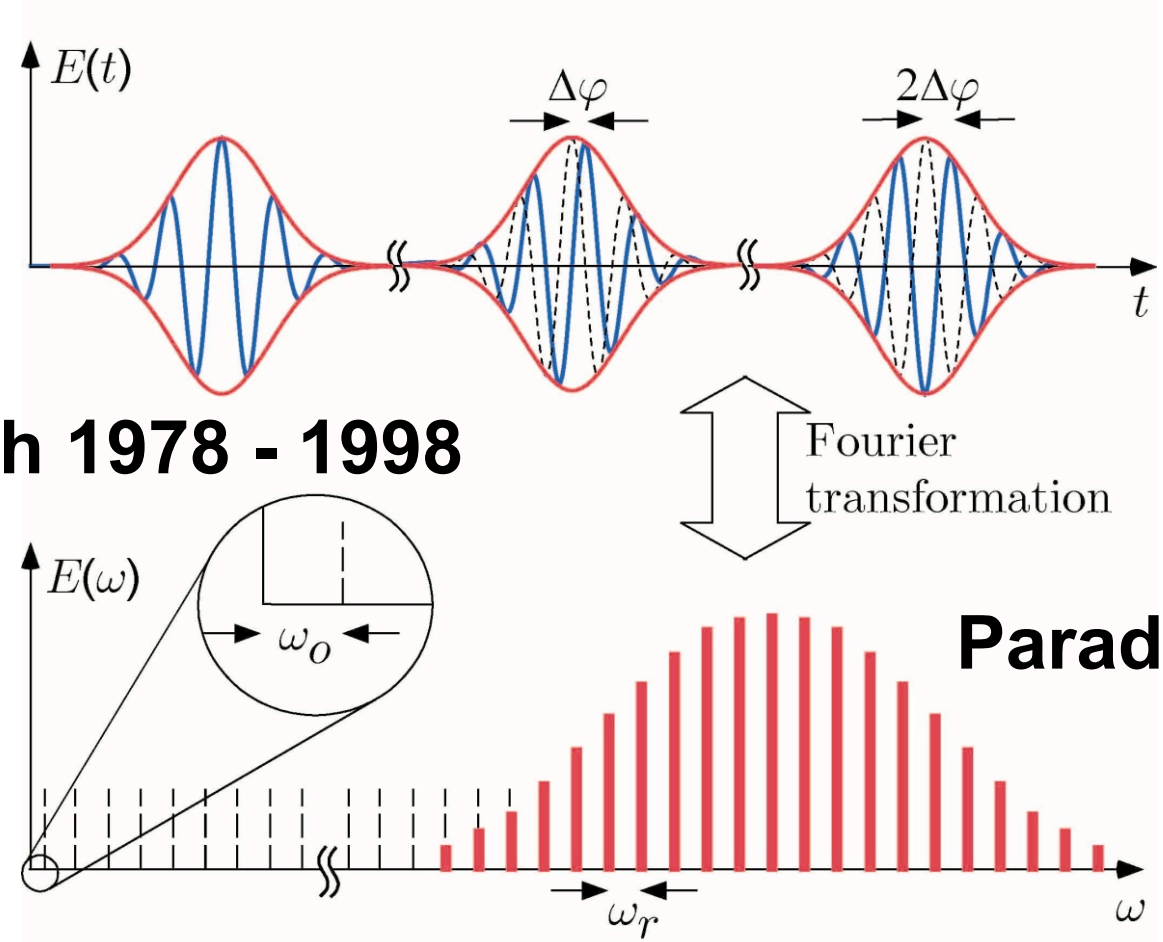
$$f = c/\lambda$$

560 000 000 000 000 oscillations per second

Pulsed Laser = Comb Generator



Frequency Combs



Ted Hänsch 1978 - 1998

Paradigm shift!

$\omega_{opt}=N\ \omega_{rep} + \omega_0$

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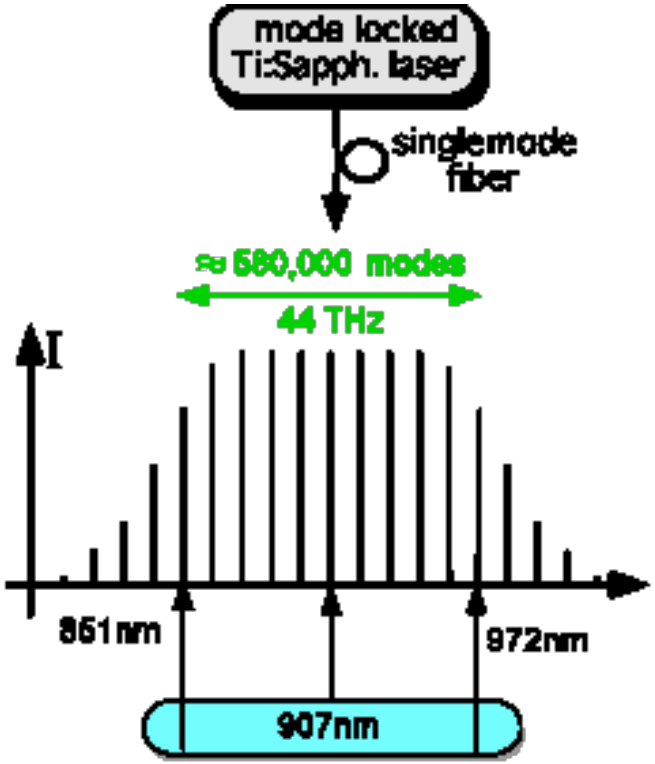
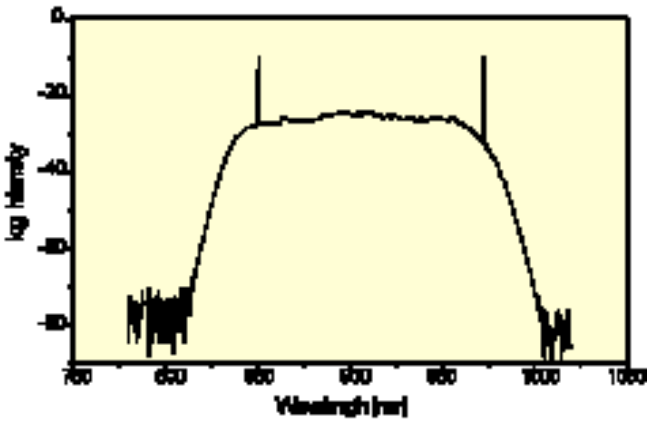
Is the Mode Spacing Equal?





Yes!

MPQ 1998

PRL 82, 3568 (1999)
OL 24, 881 (1999)

Average: 0.054± 0.111 mHz
(3×10^{-16})

From first tests to an established technique in just one decade!!

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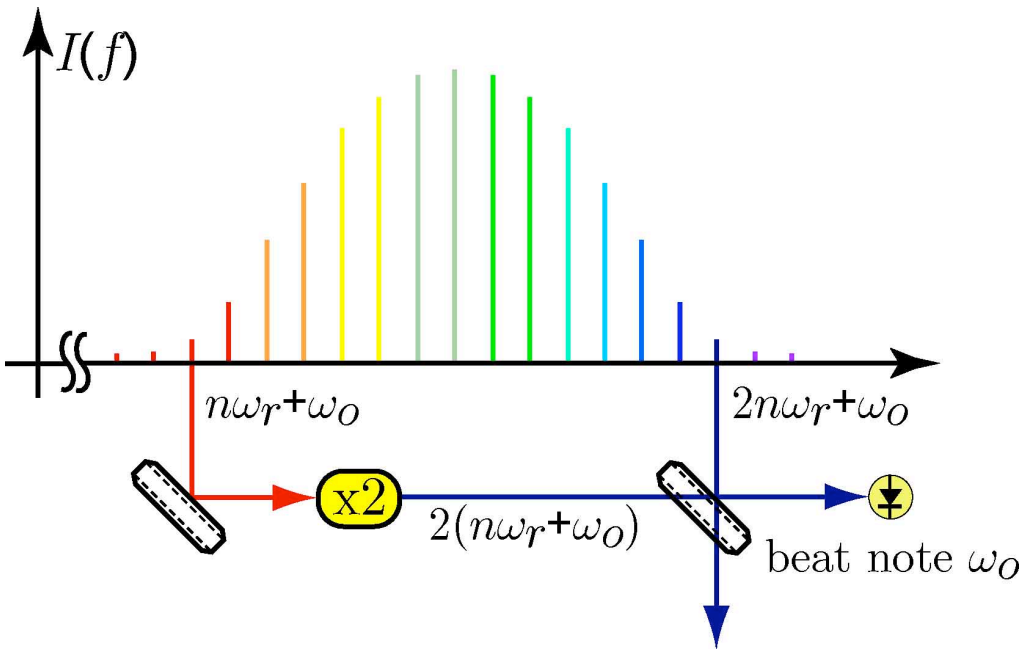
Self Referenced Laser Comb



JILA, MPQ 2000

PRL 84, 5102 (2000)
PRL 85, 2264 (2000)

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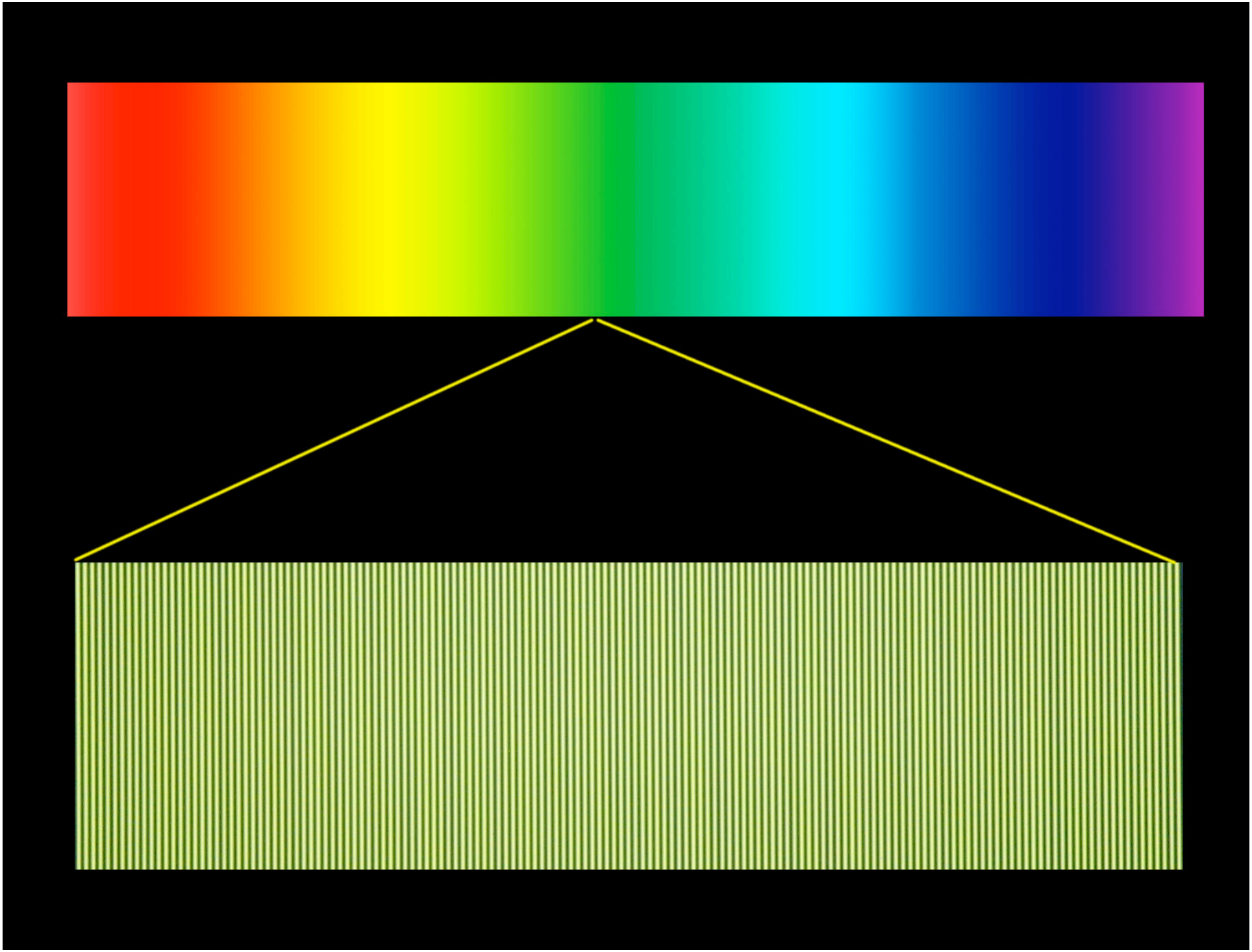
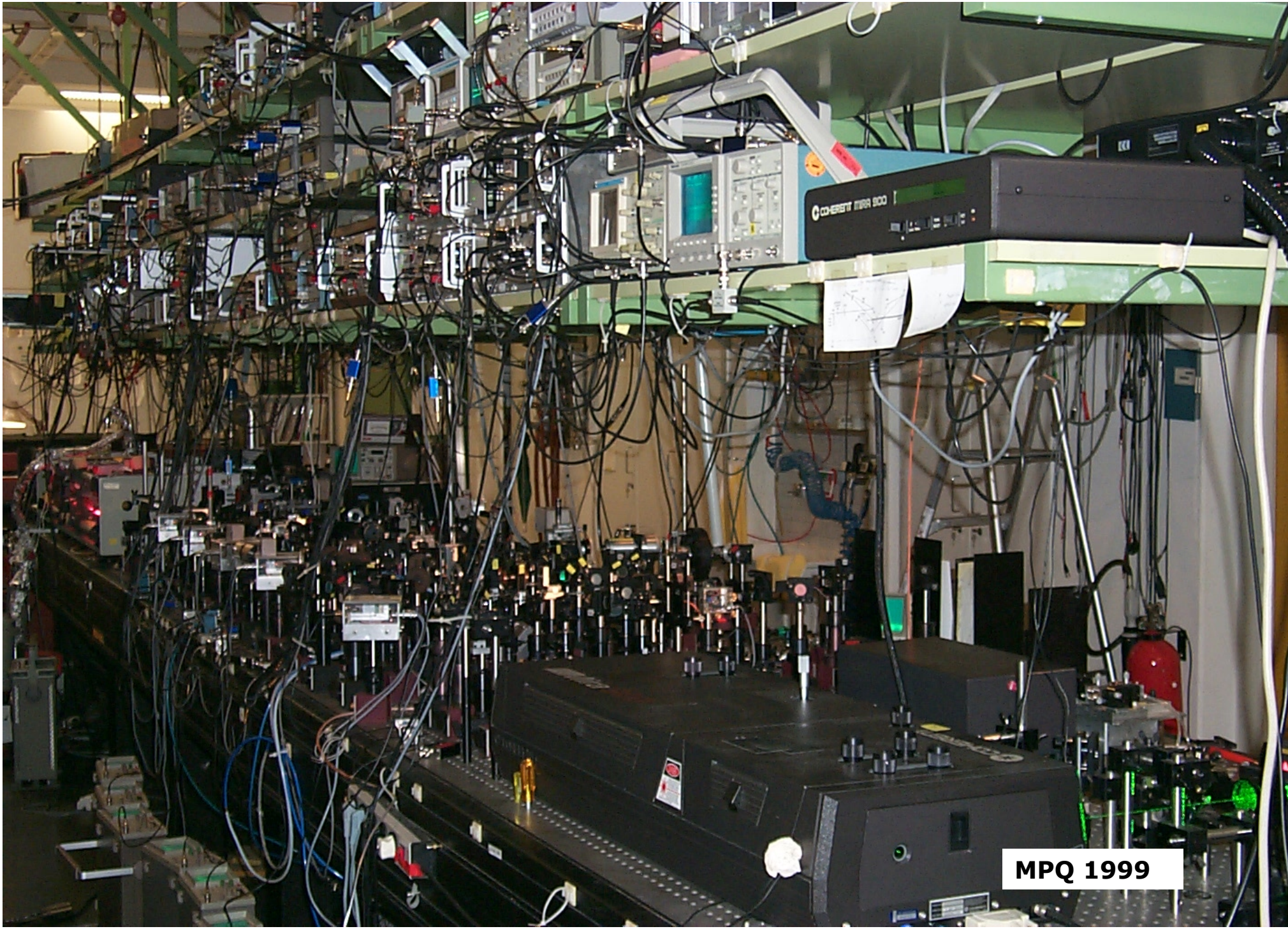
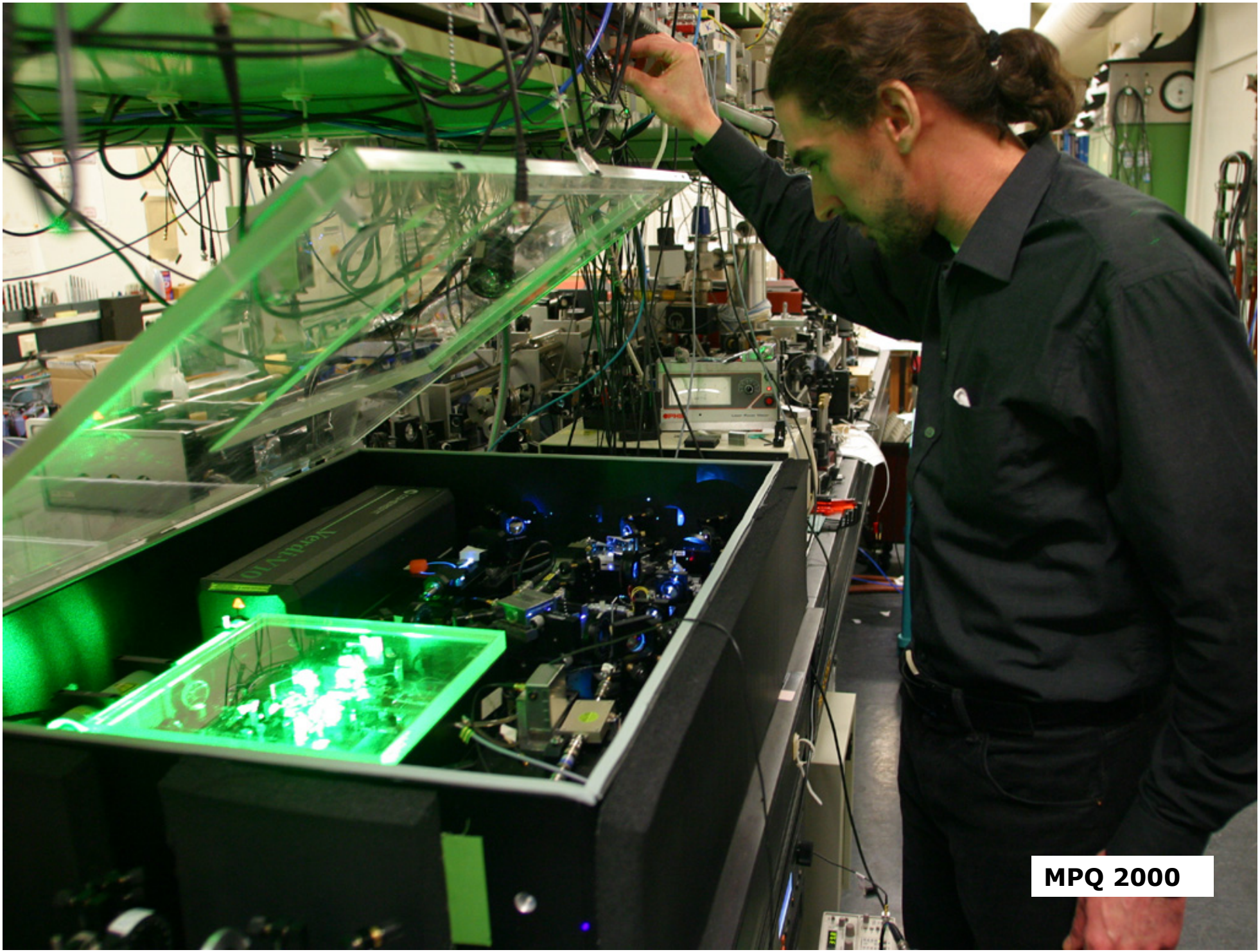


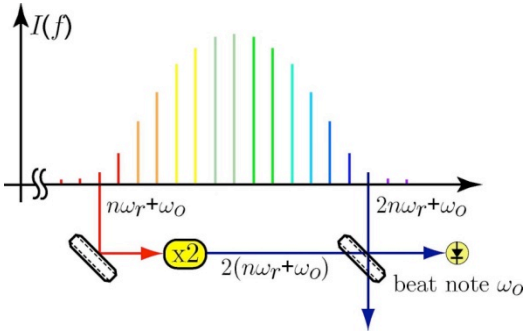

COHERENT MIRA 900
MPQ 1999


MPQ 2000

fiber comb (2005)

- Sealed “Shoe box” design for 24/7 hands off operation

Nobel Prize (2005)



The Nobel Prize in Physics 2005

John L. Hall and **Theodor W. Hänsch**

„for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique“

Frequency Comb Technology gets scientific crown

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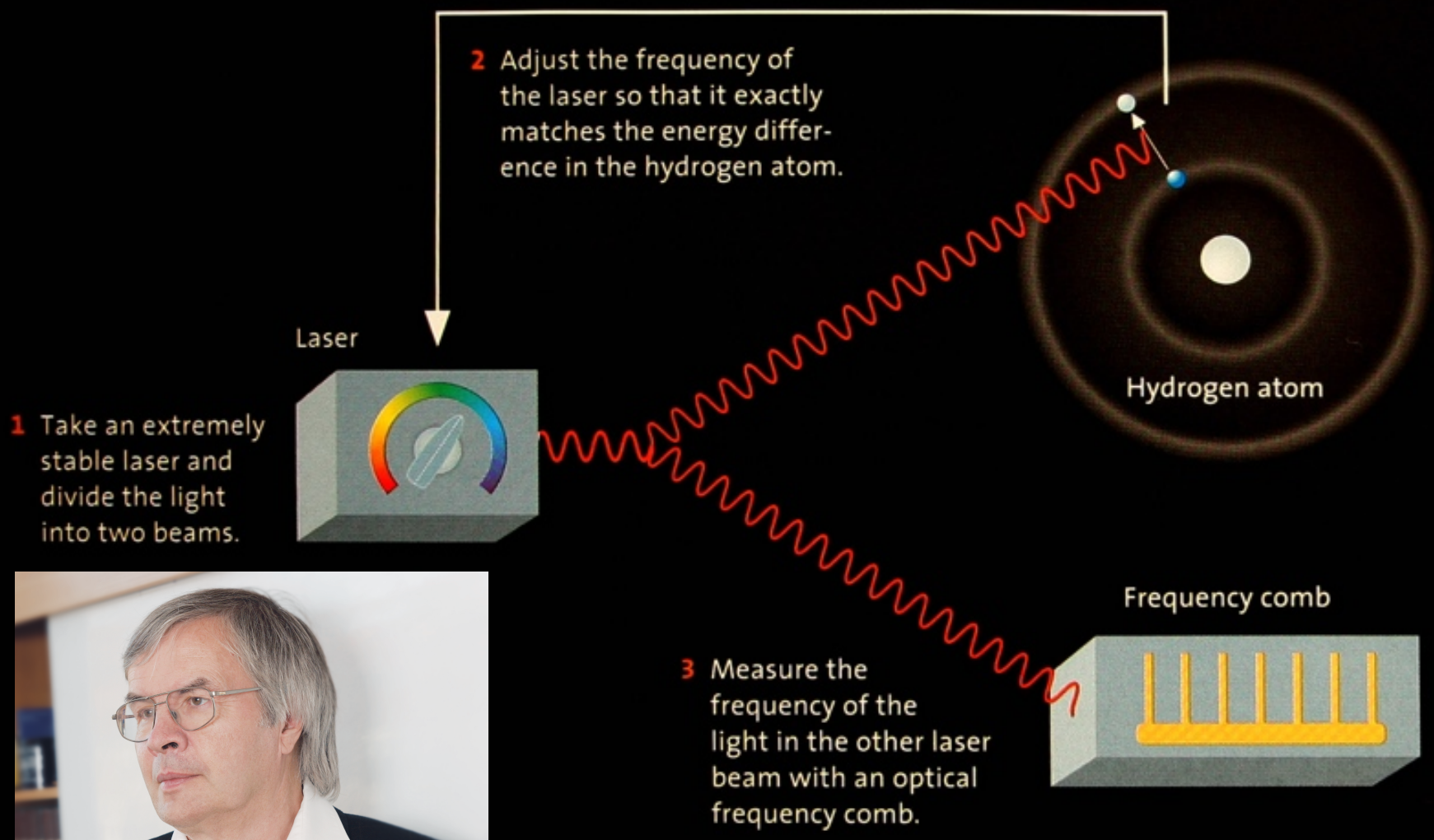
Measuring the Frequency of Hydrogen with a Laser Comb



Menlo Systems (2001)

- Spin-off from the Max-Planck-Institute for Quantum Optics (MPQ), founded in 2001.
- No outside financing (some BMBF money and customer prepayment)
- As of today: 65 employees (1/3 with PhD)
- more than 100 combs installed
- 10th anniversary in May 2011

➡ ***Bootstrapping***

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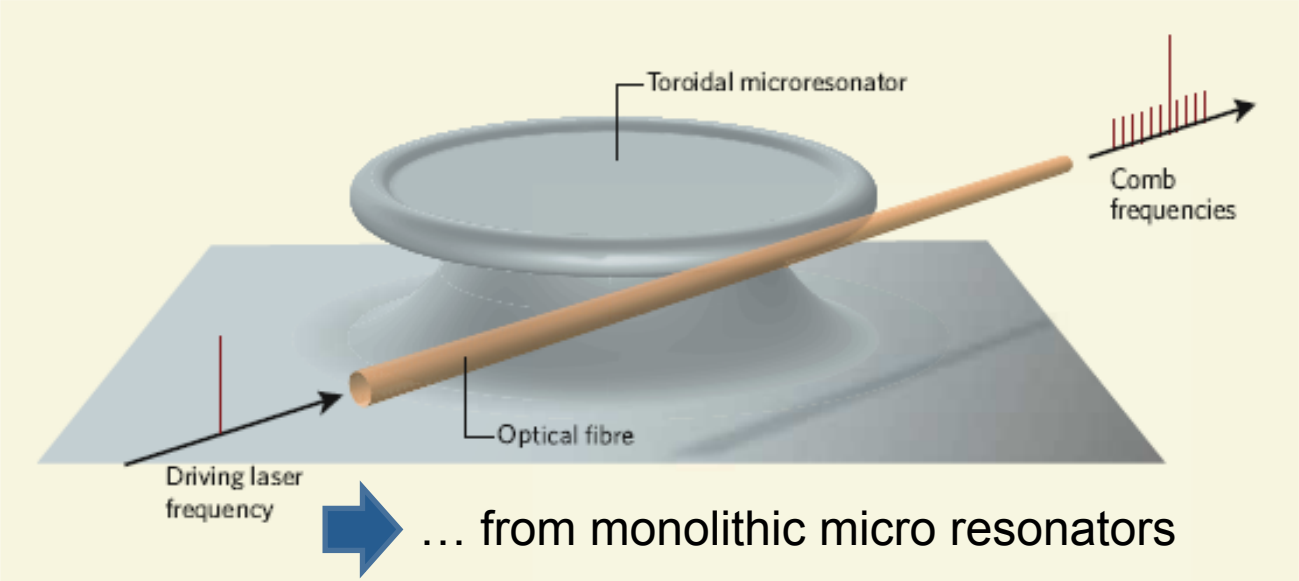
New Frequency Combs



In cooperation with EPFL:
T. Herr, J. Riemensberger
A. Schliesser, D. Arcizet, P. Del Haye (former students)
T. Kippenberg

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Funded by European Project FP 7, IAPP

T. J. Kippenberg, R. Holzwarth, S. A. Diddams, Science 2011

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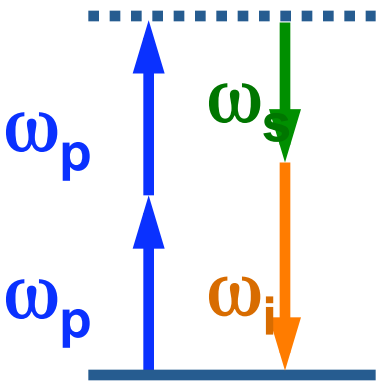
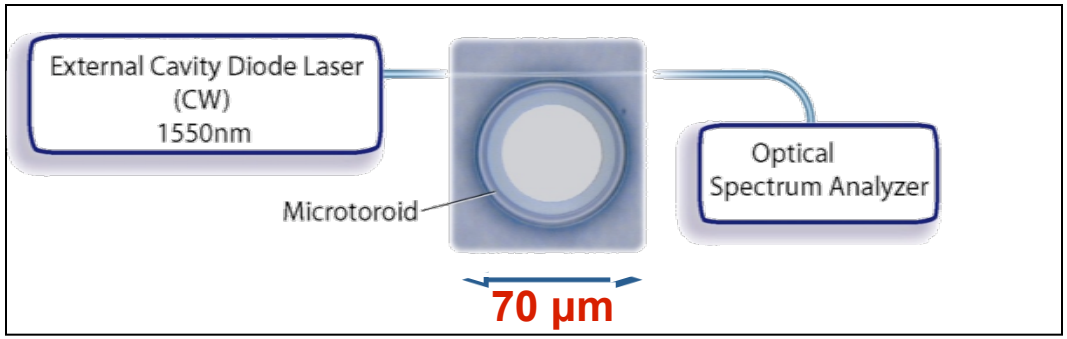
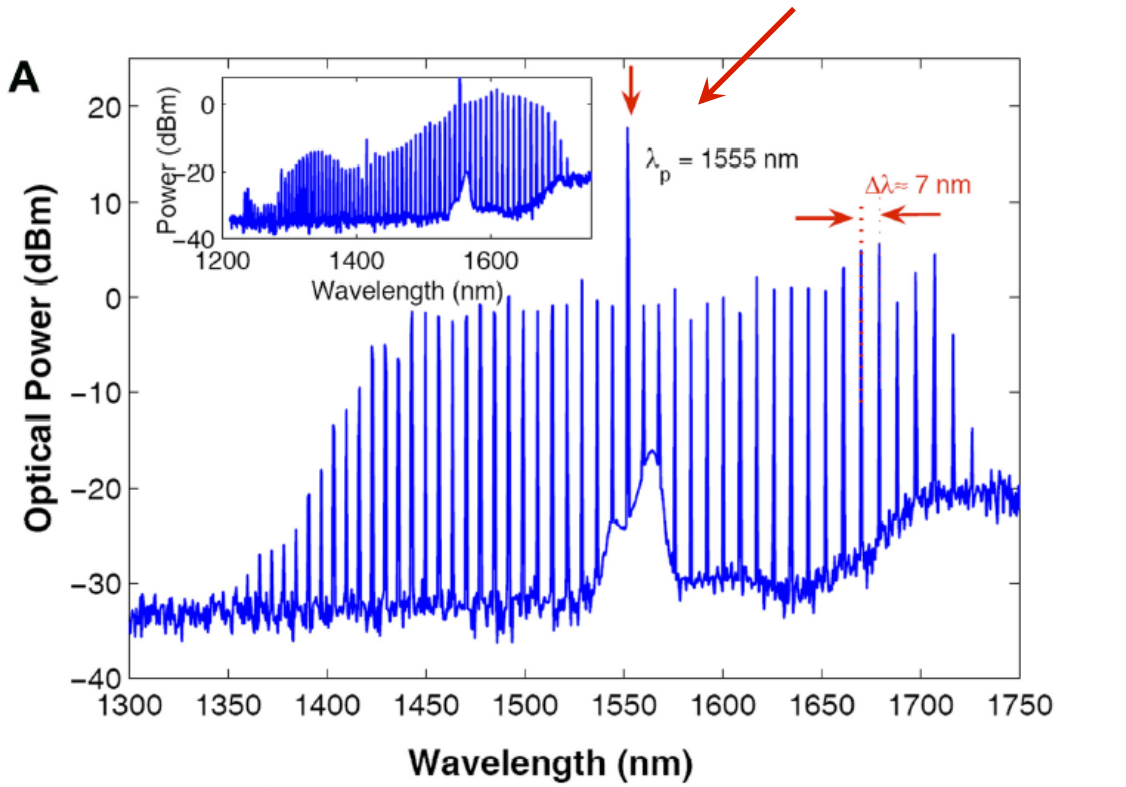
Parametric Comb Generation







- Octave spanning spectra possible
- mode spacing 80 GHz to 1 THz

Del Haye, Schliesser, Arcizet, Holzwarth, Kippenberg, Nature, Dec. 20, **2007**

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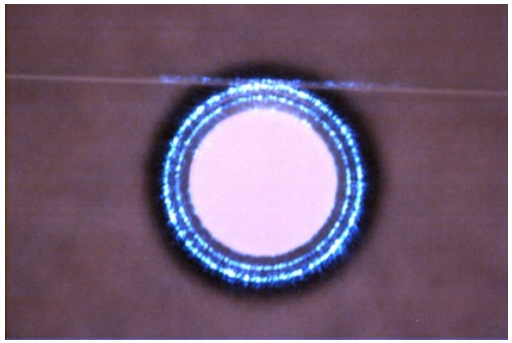
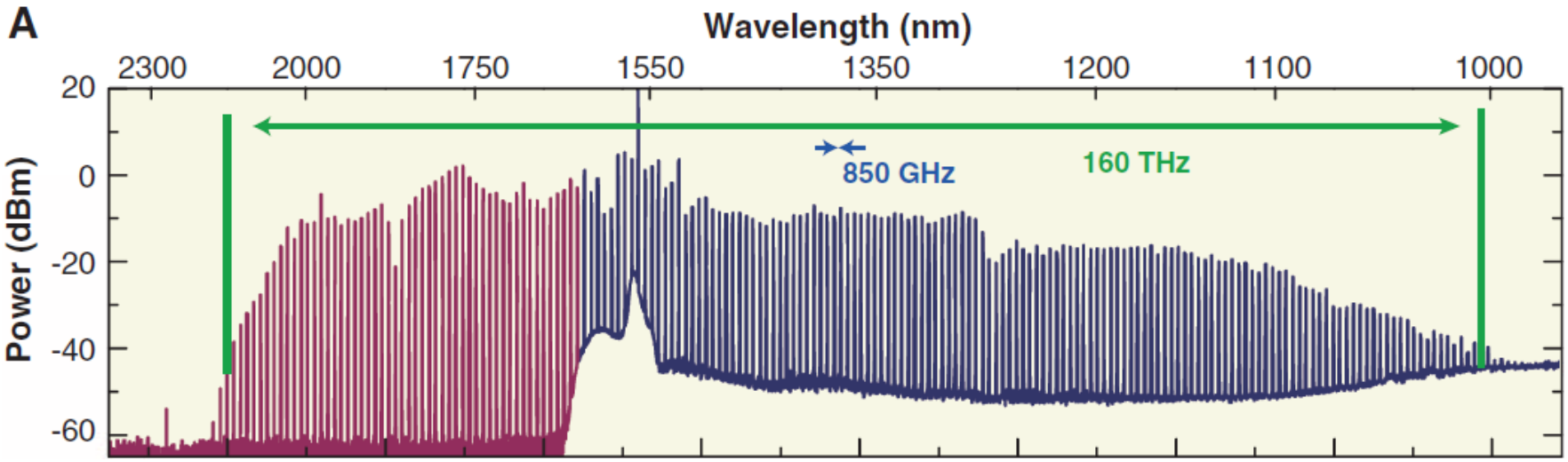
Octave Spanning Micro Comb





Calibration with Frequency Combs

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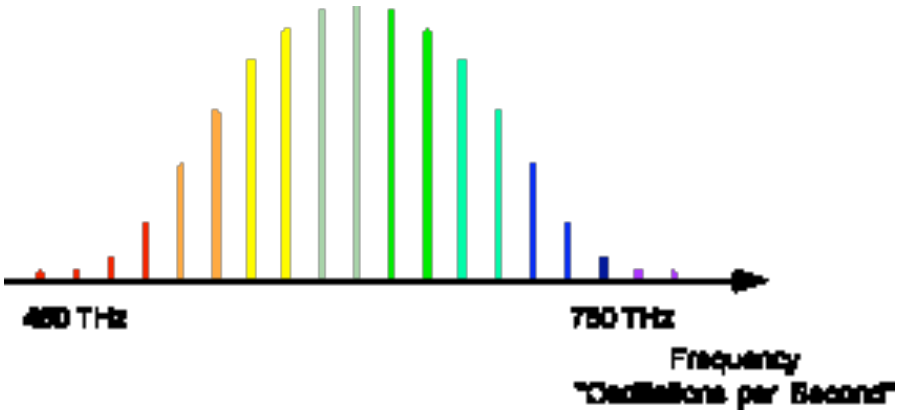


Astronomical Precision Spectroscopy

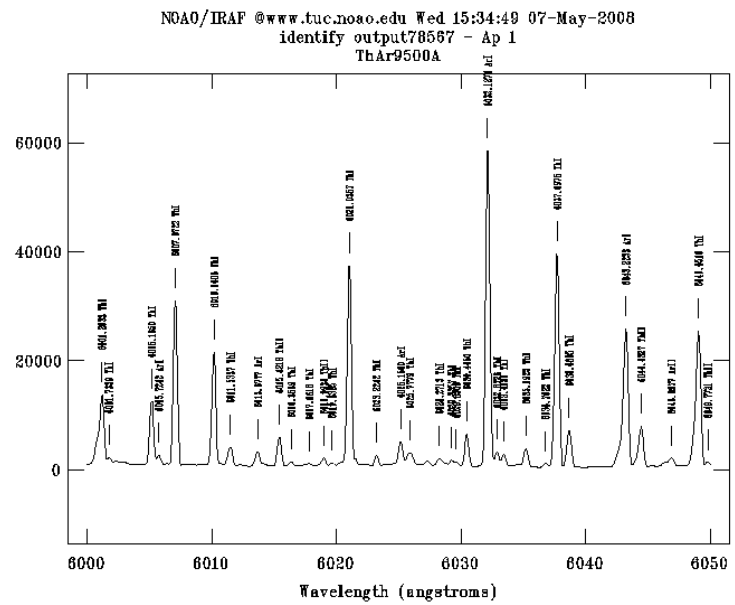
	Required precision		
• **Detection of extra solar Earths**	$2x10^{-10}$	~5 cm/s	~100 kHz
• **Acceleration of cosmic expansion**	$4x10^{-11}$	~1 cm/s	~20 kHz

- **Calibration must be reproducible over years / decades!**

Calibration Sources

- **Traditional calibration sources (e.g. Th-Ar spectral lamps) achieve presently ~2x10^{-9}, but have major drawbacks:**

Th-Ar lamp
Lines differ in intensity and spacing
Fixed line positions
Ar ions are sensible to lamp pressure changes.
Lamp ages
Accuracy limited to ~10^{-9}



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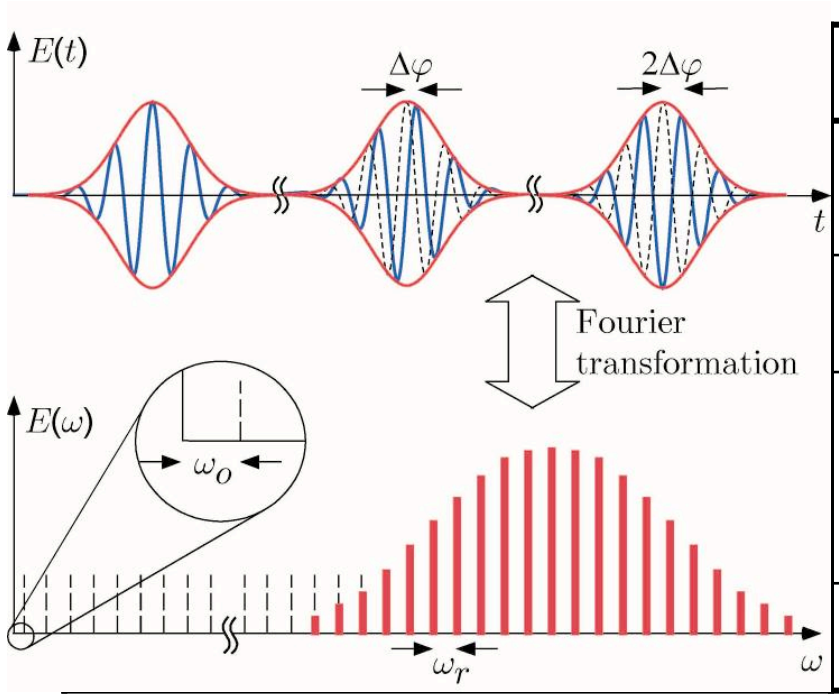
Calibration Sources

- **A specifically designed frequency comb overcomes all these problems and has the potential for mm/sec precision!**



Frequency comb
Uniform mode spacing and intensity
Tunable line positions
Reference to atomic clock: does not change with time
Accuracy limited to ~10^{-15}

Comb vs. Th Ar

Th-Ar lamp ☹	Frequency comb ☺
Lines differ in intensity and spacing	Uniform mode spacing and intensity
Fixed line positions	Tunable line positions
Ar ions are sensible to lamp pressure changes.	Reference to atomic clock: does not change with time
Lamp ages	
Accuracy limited to ~10^{-9}	Accuracy limited to ~10^{-15}

Frequency Comb Specs

Fs Lasers as comb generators
100 MHz to 1 GHz mode spacing
Most spectrographs: R = 20 000 to 100 000 or 5 GHz to 20 GHz

needs filtering

Comb Accuracy:
relativ: 10^{-12} to 10^{-15} from commercial clocks
absolut: 500 Hz to 0.5 Hz at 500THz (green)
In RV: 200 µm/sec to 200 nm/sec

1 m/s ~ 2 MHz ~ 0.002pm

$$v = \frac{\Delta f}{f} c = \Delta f \cdot \lambda$$

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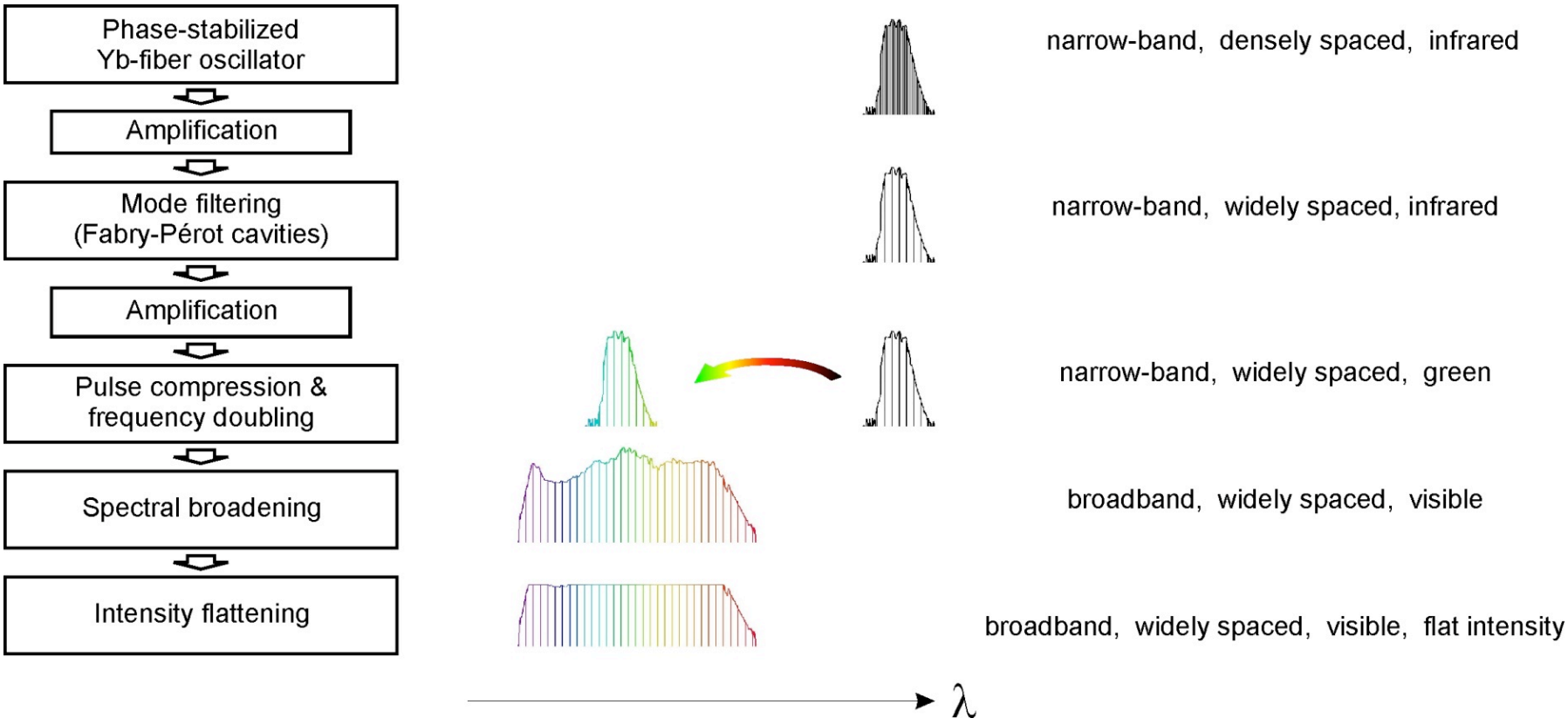
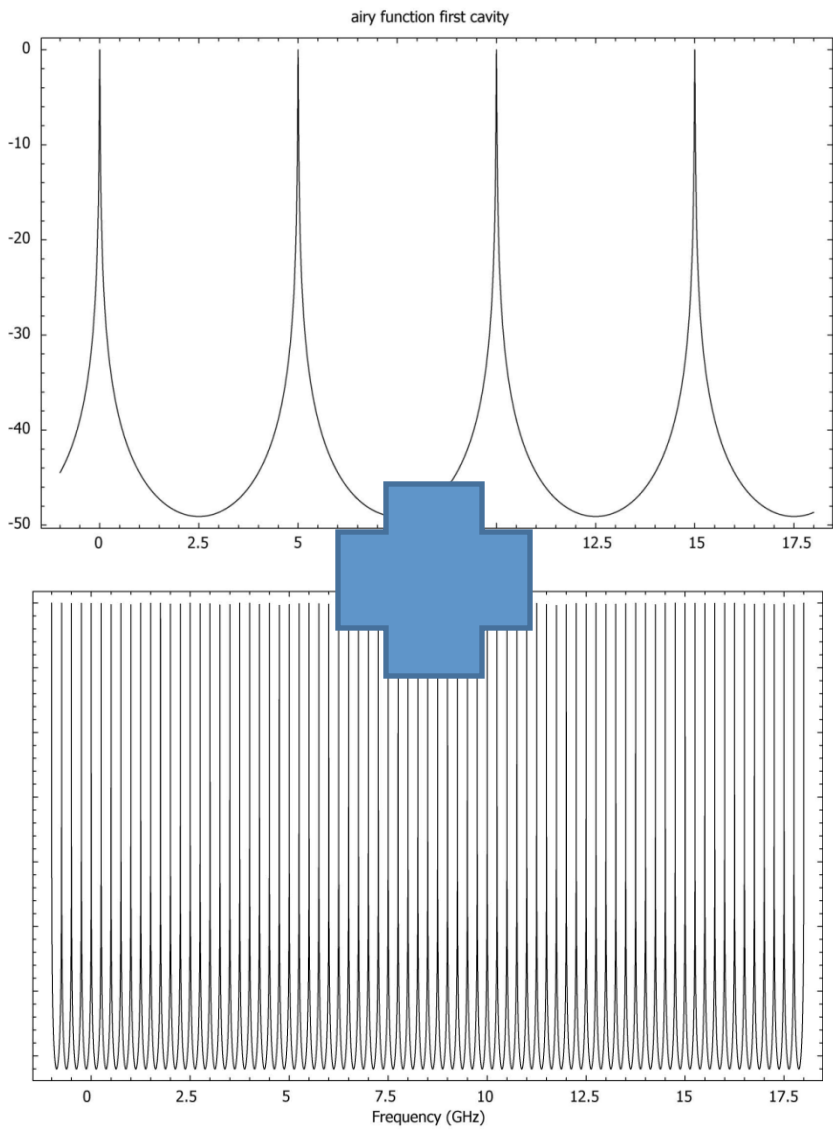
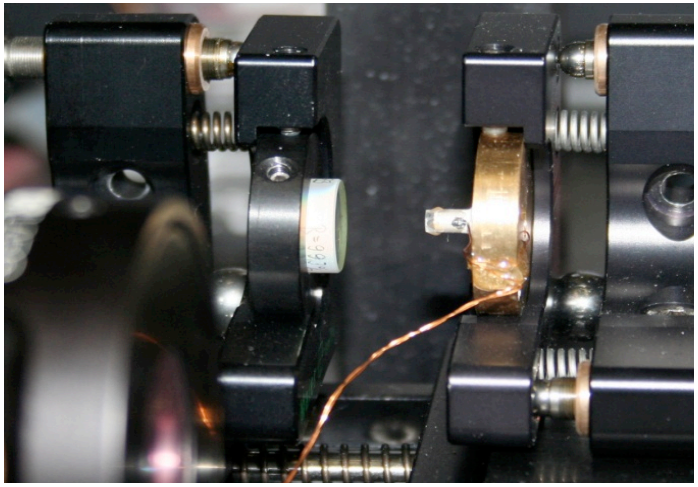
Astro comb system overview



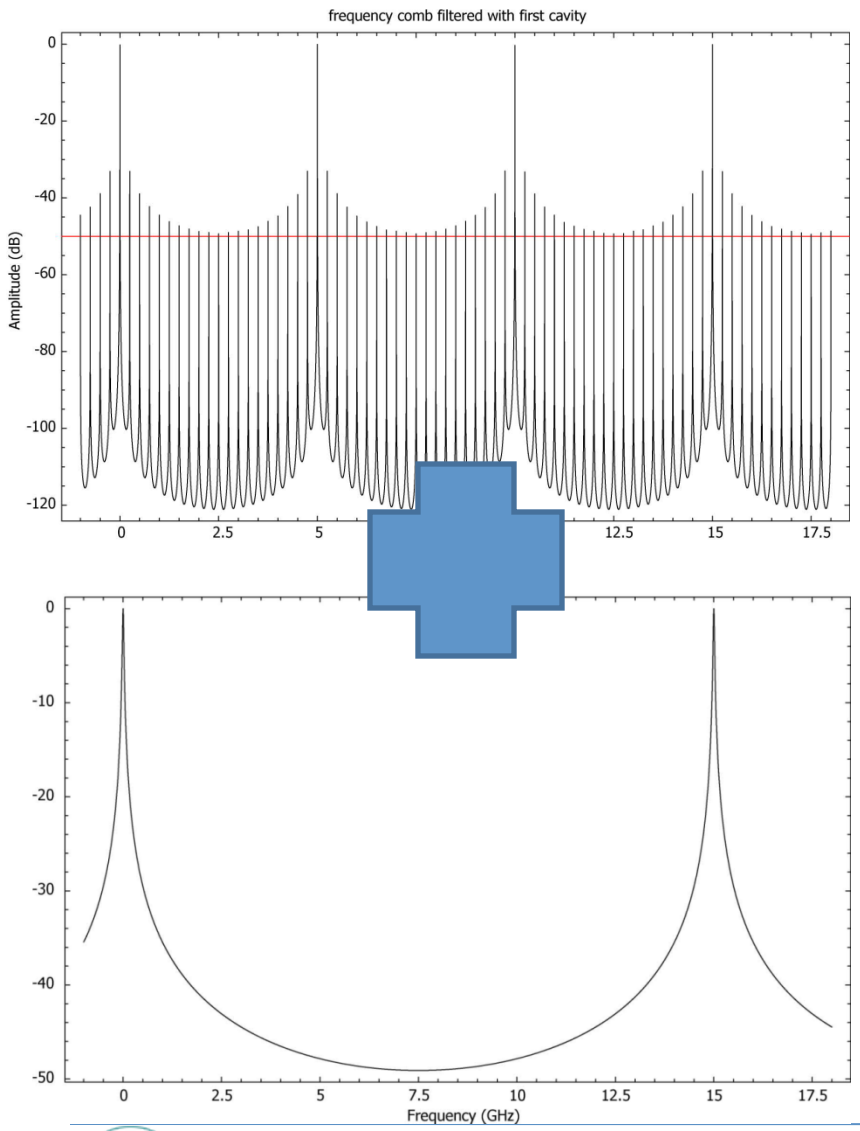
Filtering the Comb

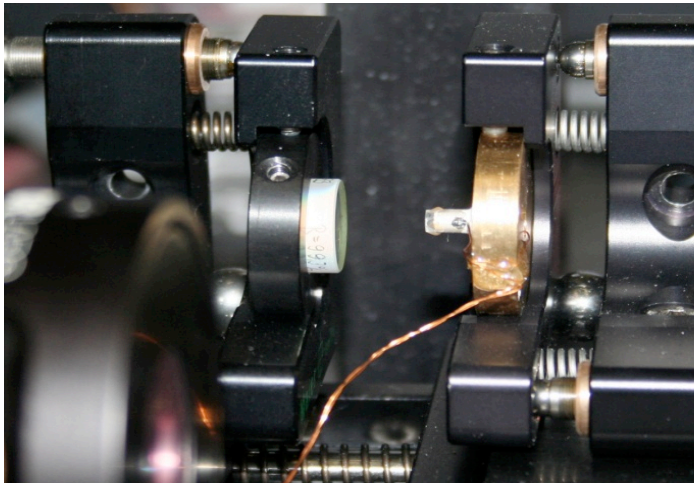




18 GHz

Filtering the Comb





18 GHz

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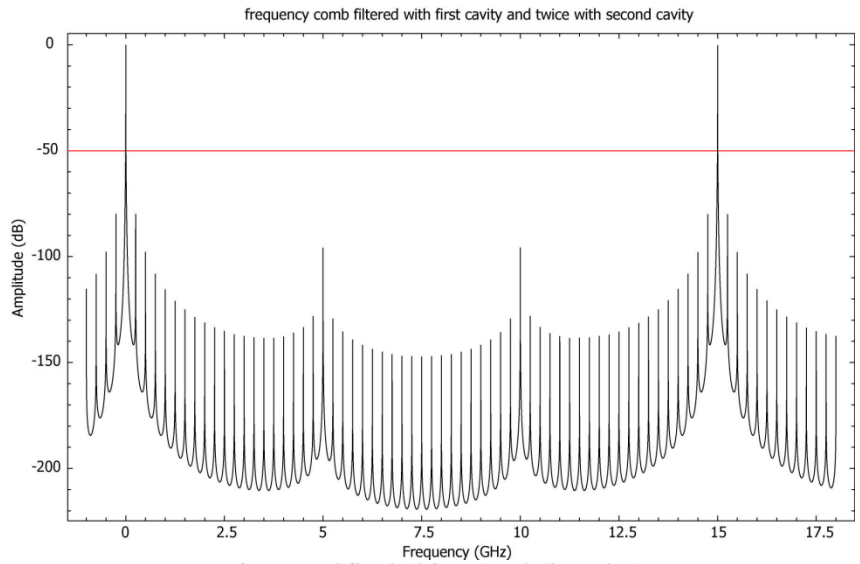
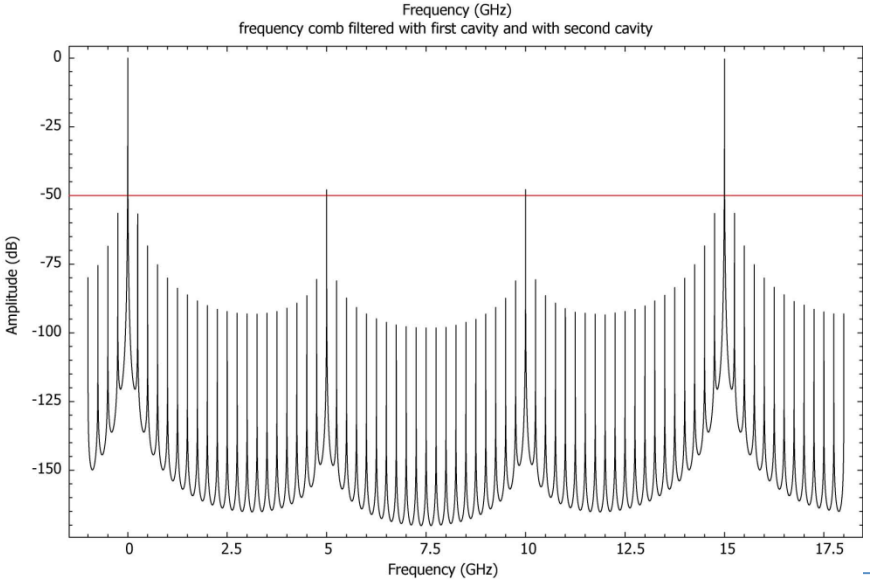
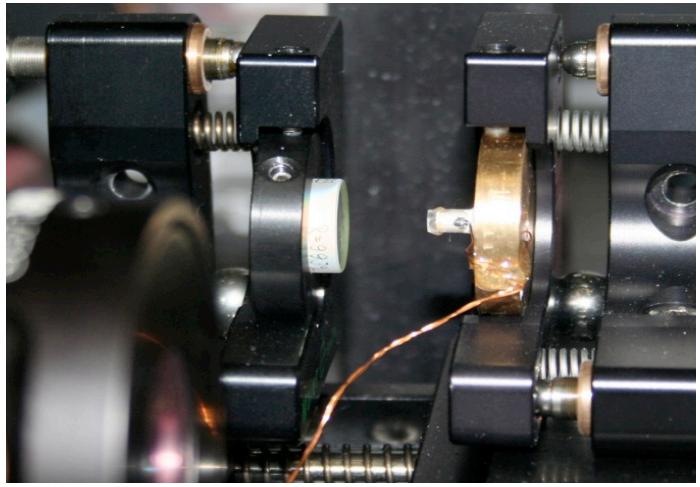
Filtering the Comb







18 GHz

Measured side mode supression:
Single Pass: 42 dB
Double Pass: 80 dB

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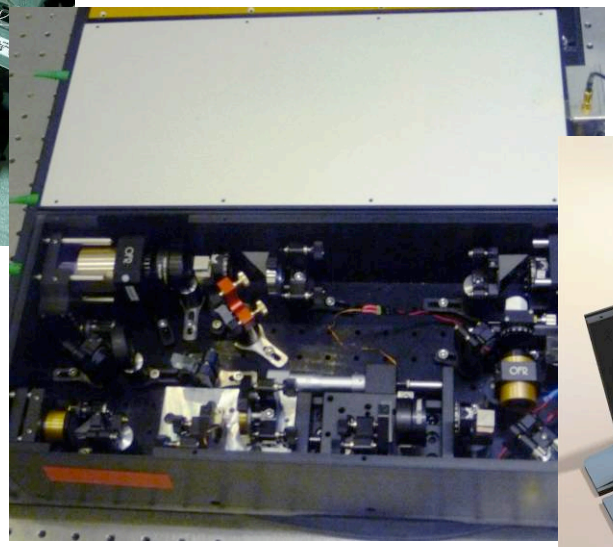
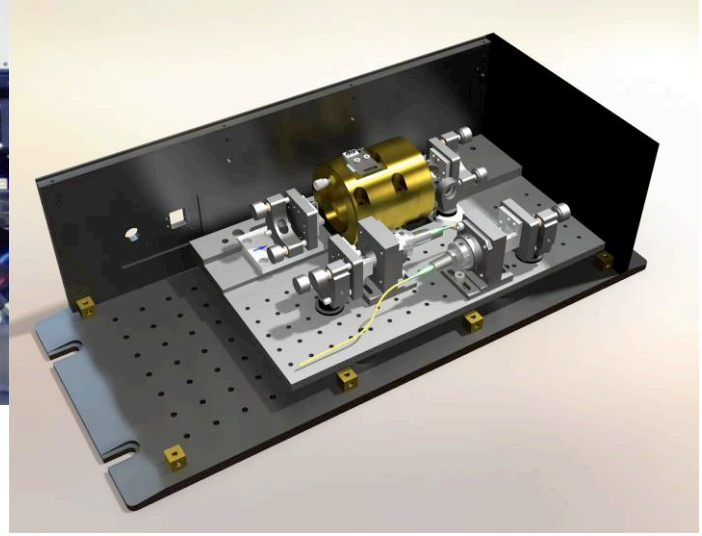
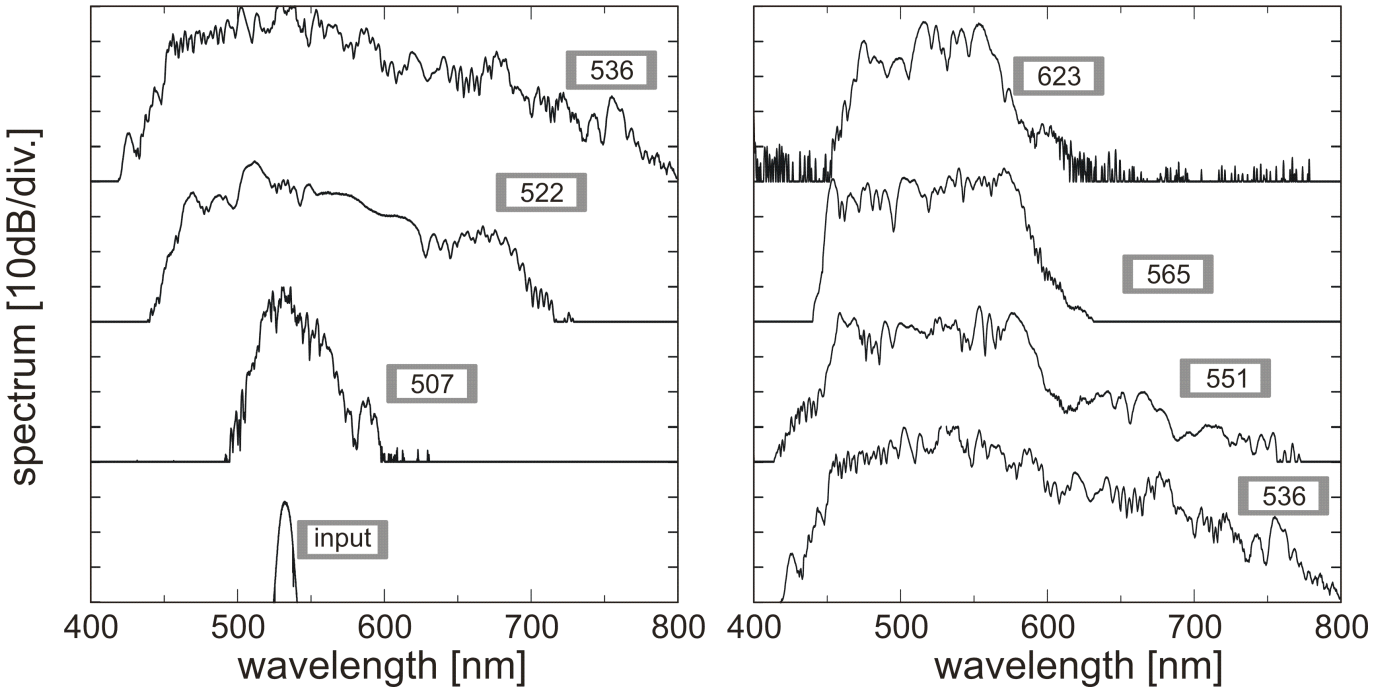
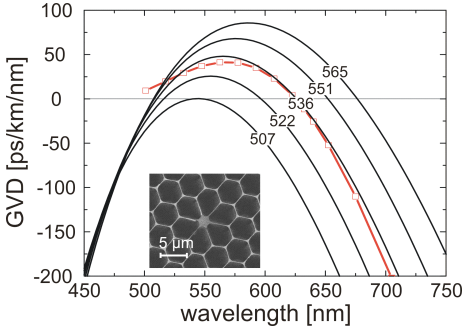
Mode Filter Cavitites





Spectral broadening





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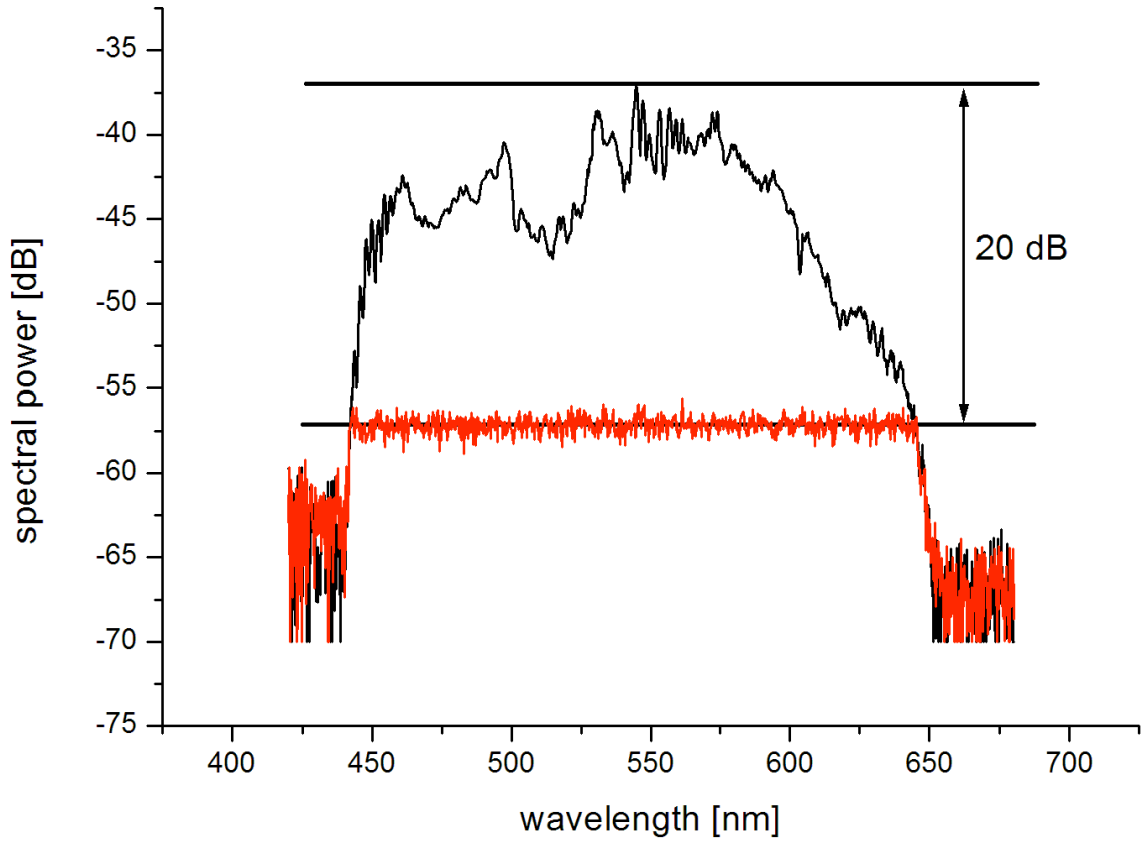
Flattened Spectrum

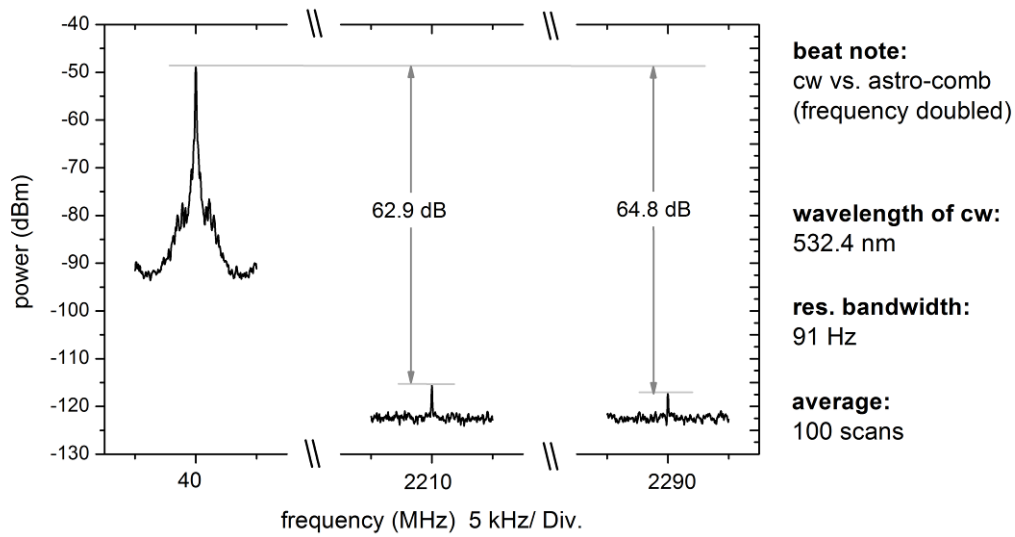


Side mode supression

Beat measurement with 3 cavities:

- broadened comb ($\Delta\lambda \approx 100$ nm)
- f_{rep}=18 GHz

- Sidemode reamplification by 15 dB

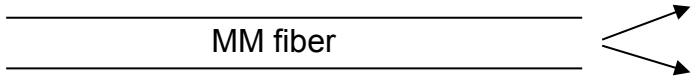


50 dB suppression after broadening in PCF

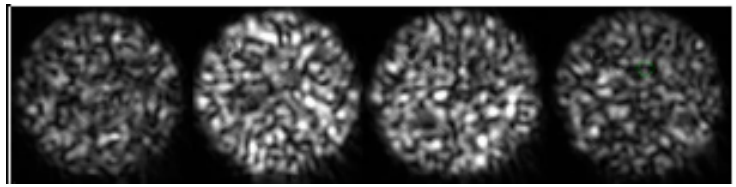
→ maximum drift < 1 cm/s

Delivery Fiber Investigation

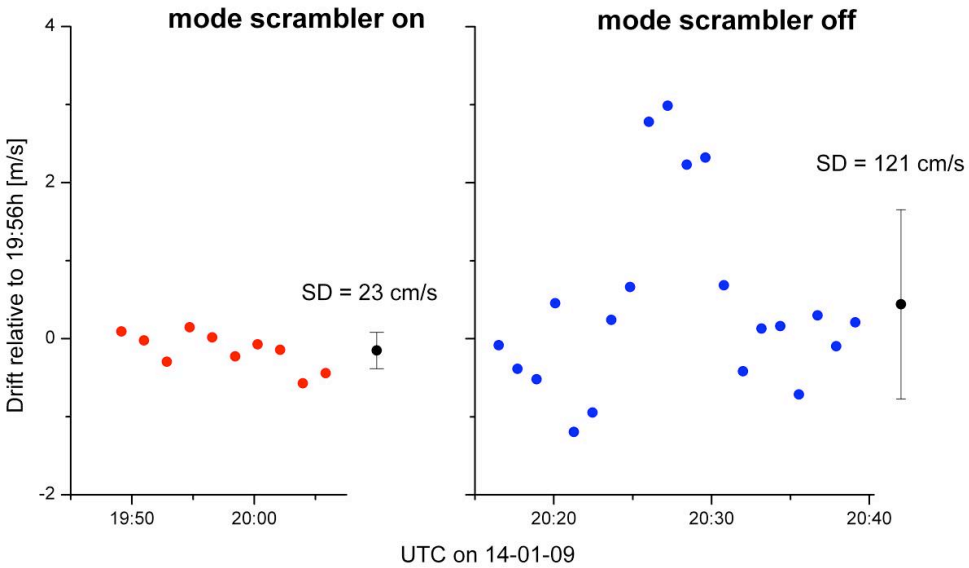
- Incoherent effect: pupil illumination



- Coherent effect: multi mode interference



Corbett & Smith, Proc. of SPIE 6269



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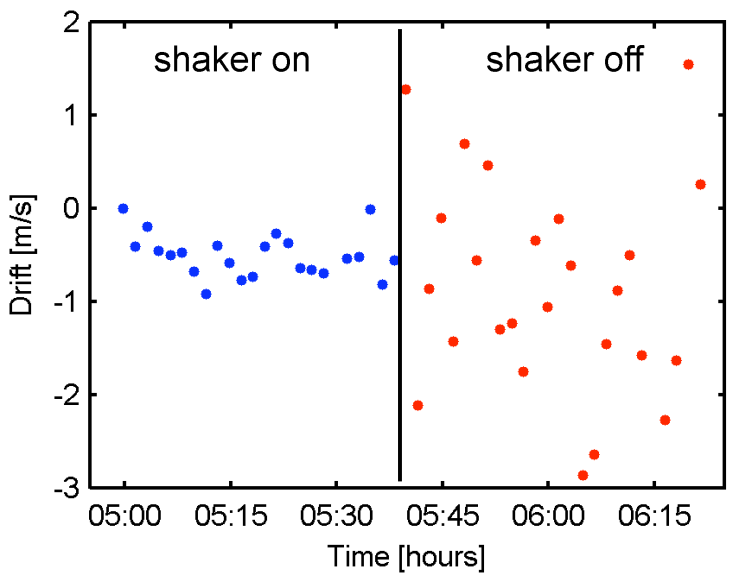
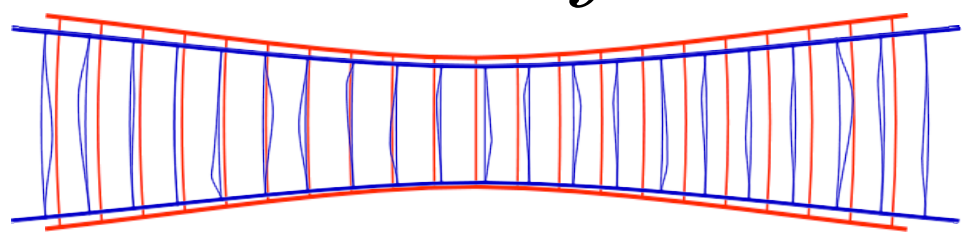
Wavefront distortion

- **Multimode fibers** guide many (>10^4) spatial modes.
- The electric field's center of gravity must be repeatable within 10^{-5}.
- A varying occupation of the spatial modes induces line shifts.



$$\lambda \neq \frac{c}{f}$$



- A mode scrambler (fiber shaker) must be implemented.

Calibration with Frequency Combs

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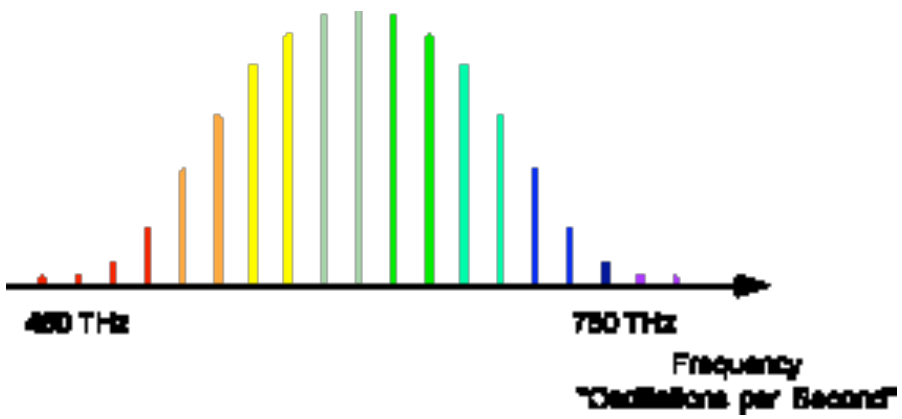
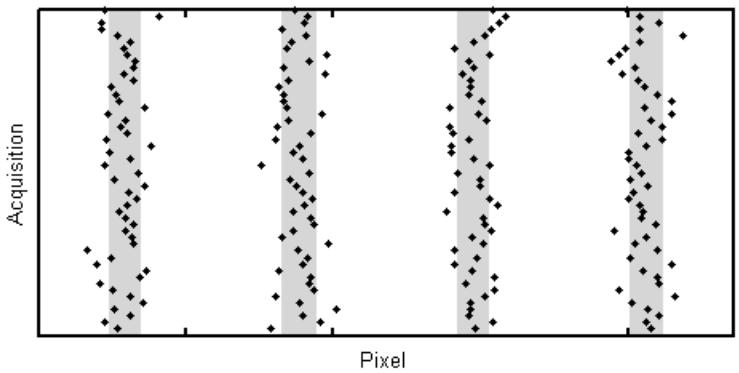


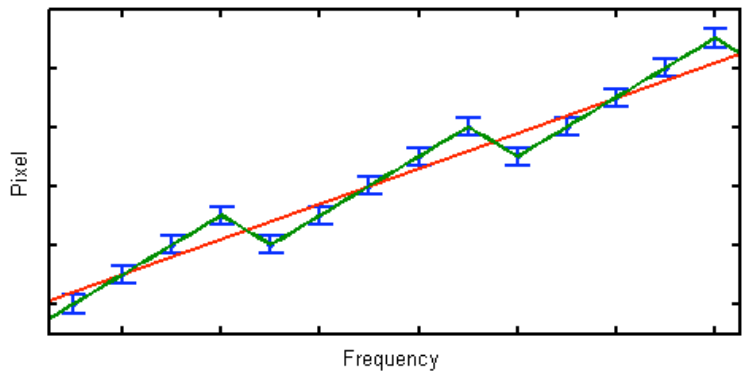
Calibration Characteristics

Repeatability



The calibration's repeatability is determined by the standard deviation of successive measurements of the same line's position on the CCD.

Absolute calibration



The deviation of a model of the pixel-to-frequency map from the measured line positions determines the calibration's absolute accuracy.

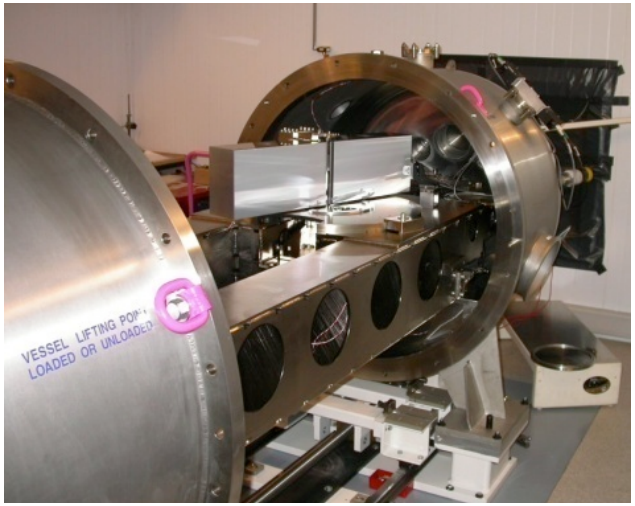
HARPS at La Silla

HARPS at the 3.6m La Silla Telescope

HARPS = High Accuracy Radial velocity Planetary Search

- Cross dispersed Echelle
  - Grating 200 x 800 mm

- Wavelength Range: 378 -691 nm (68 orders)
- Resolution: 120 000 (5 GHz @ 520 nm)
- Fibre fed (2 fibres)
- In vacuum, mK temp. stability
- Detectors: mosaic of 2 CCDs (2k x 4k)
  - 15 um pixel size
  - Actively cooled by cryostat



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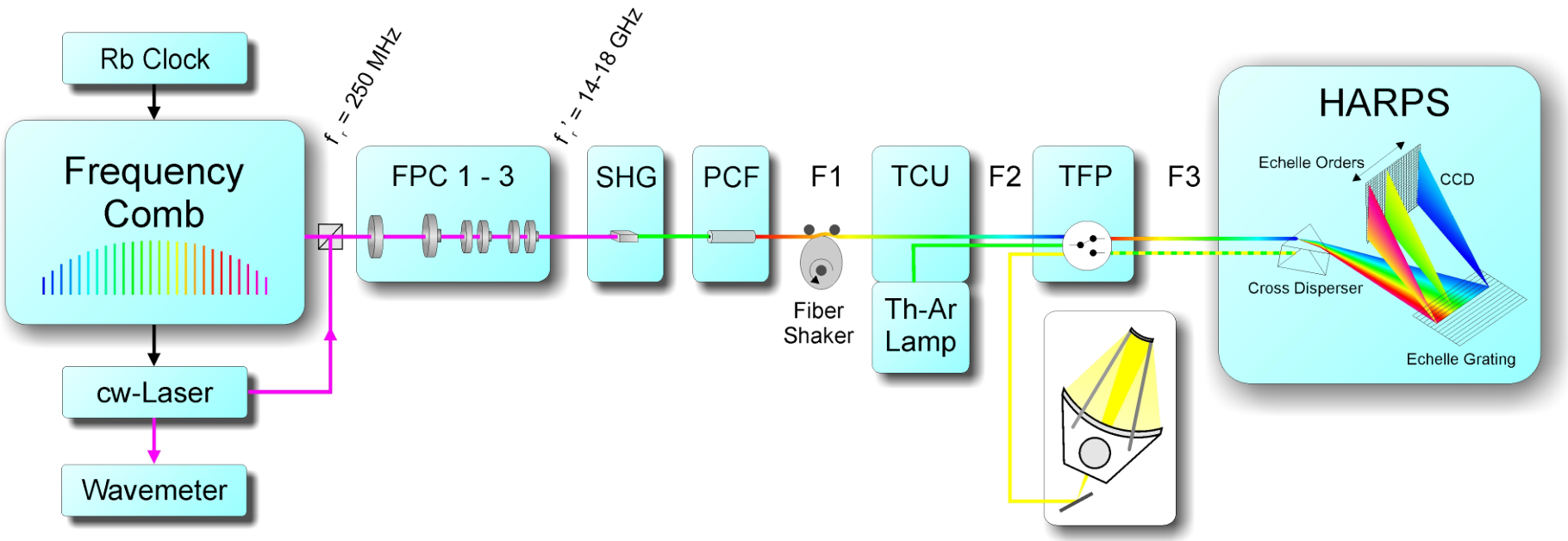
Comb for HARPS



Wavelength range: 525 ± 5.5 nm (± 50 nm)

Mode spacing: 14 -18 GHz

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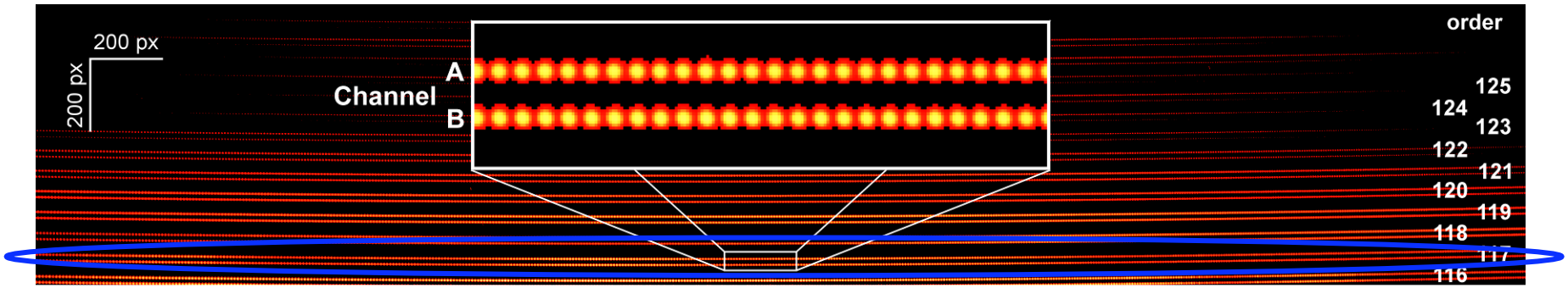
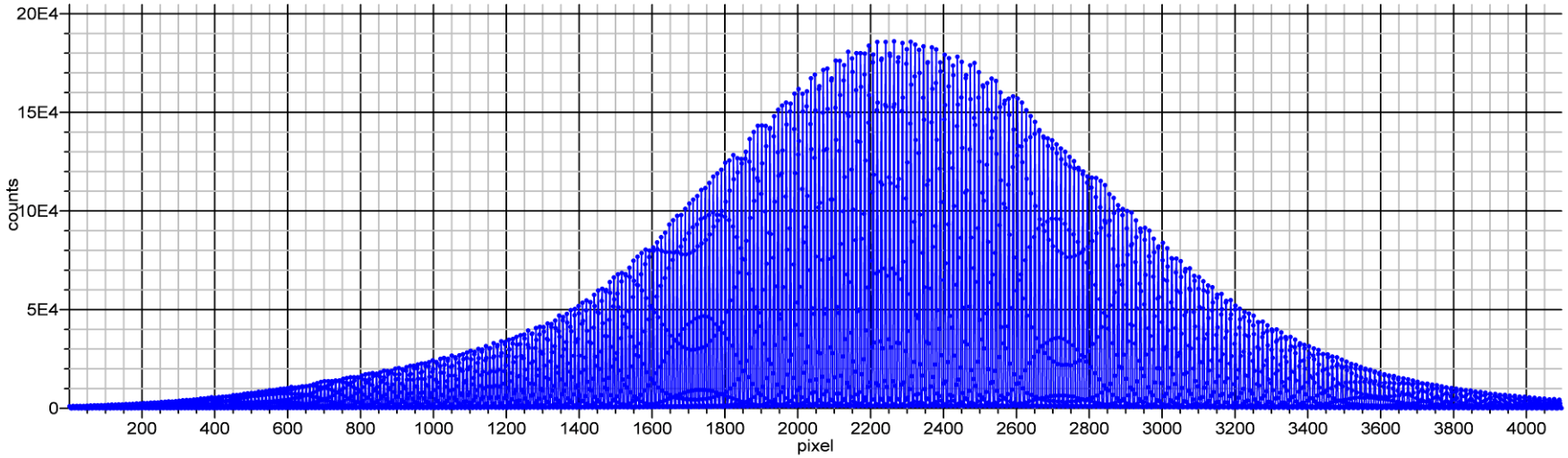
Comb Spectrum on the CCD





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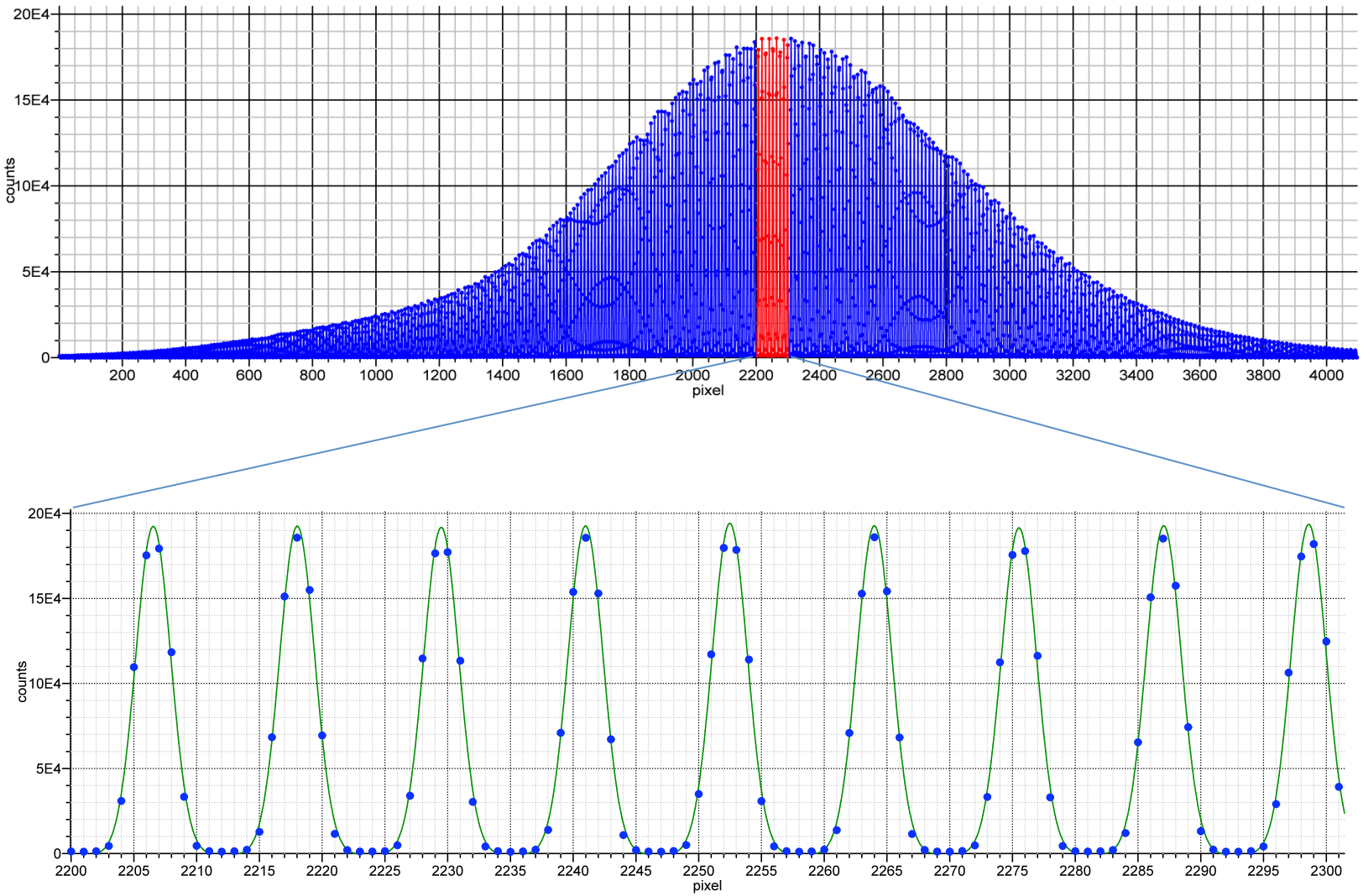
Comb Spectrum



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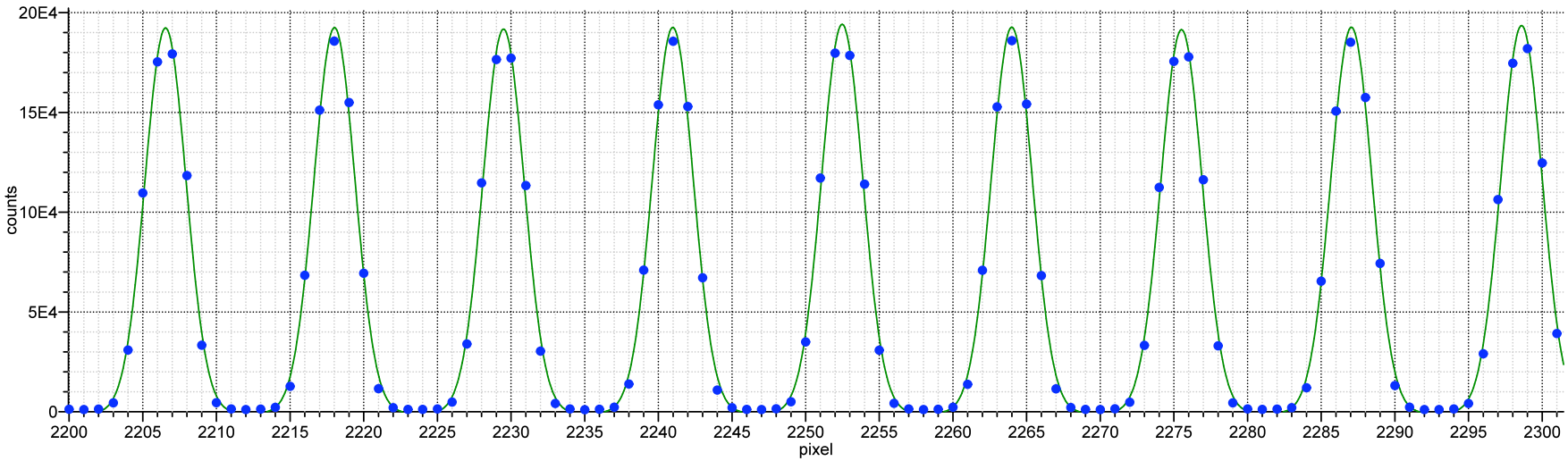
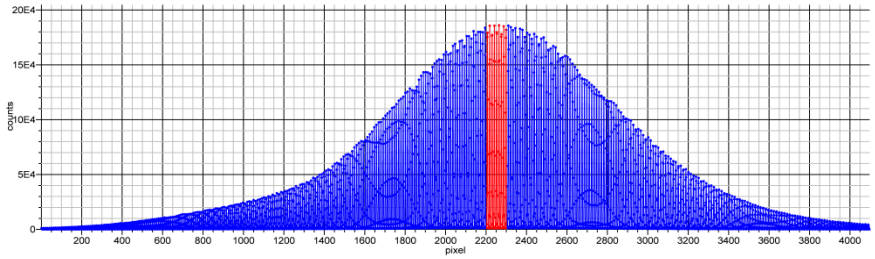
Fitting the lines



Fit functions:

350 – 450 individual Gaussians



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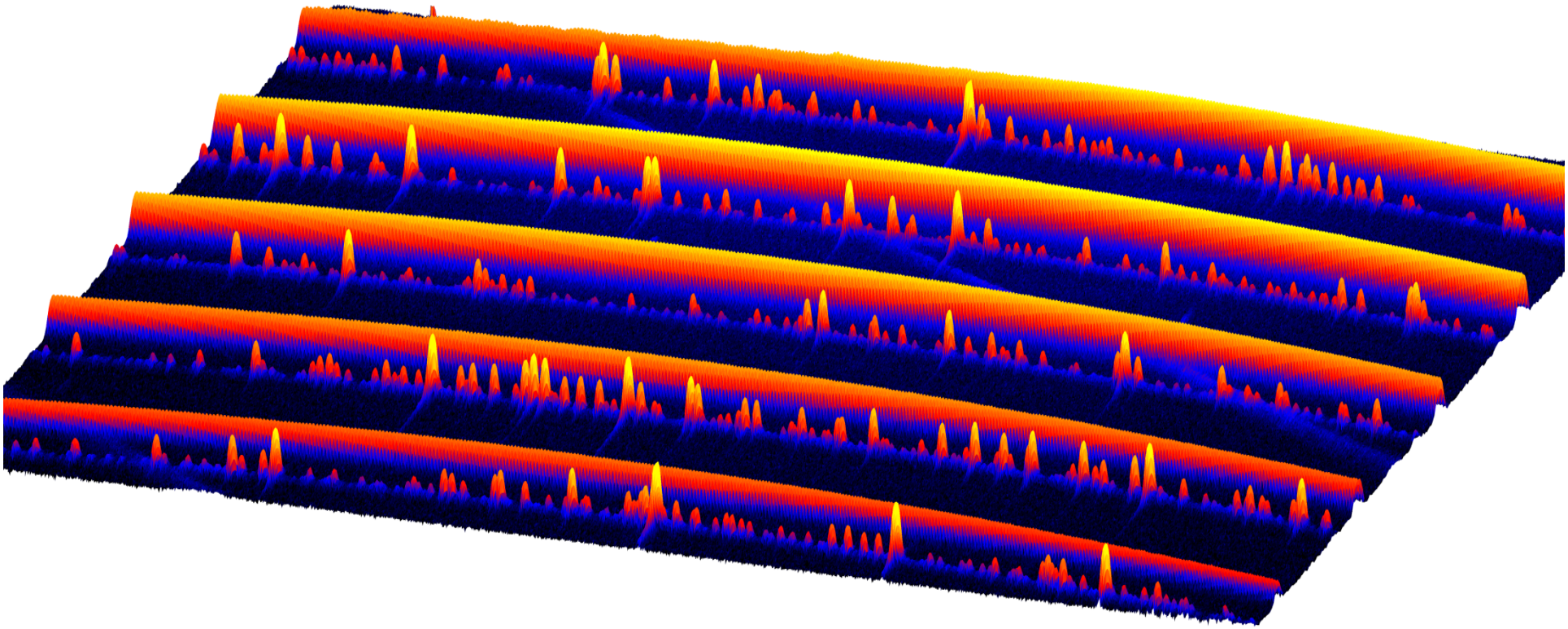
Comb and Th Ar on CCD



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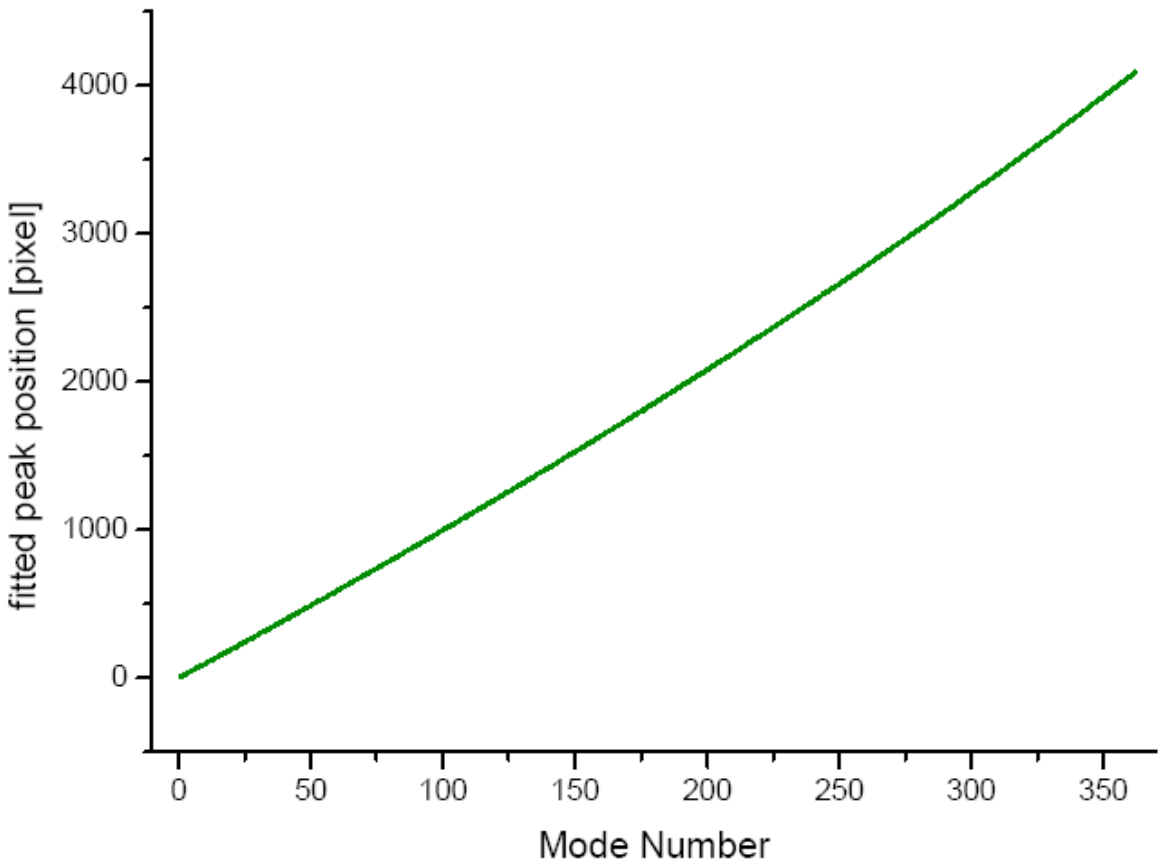
Pixel to frequency map



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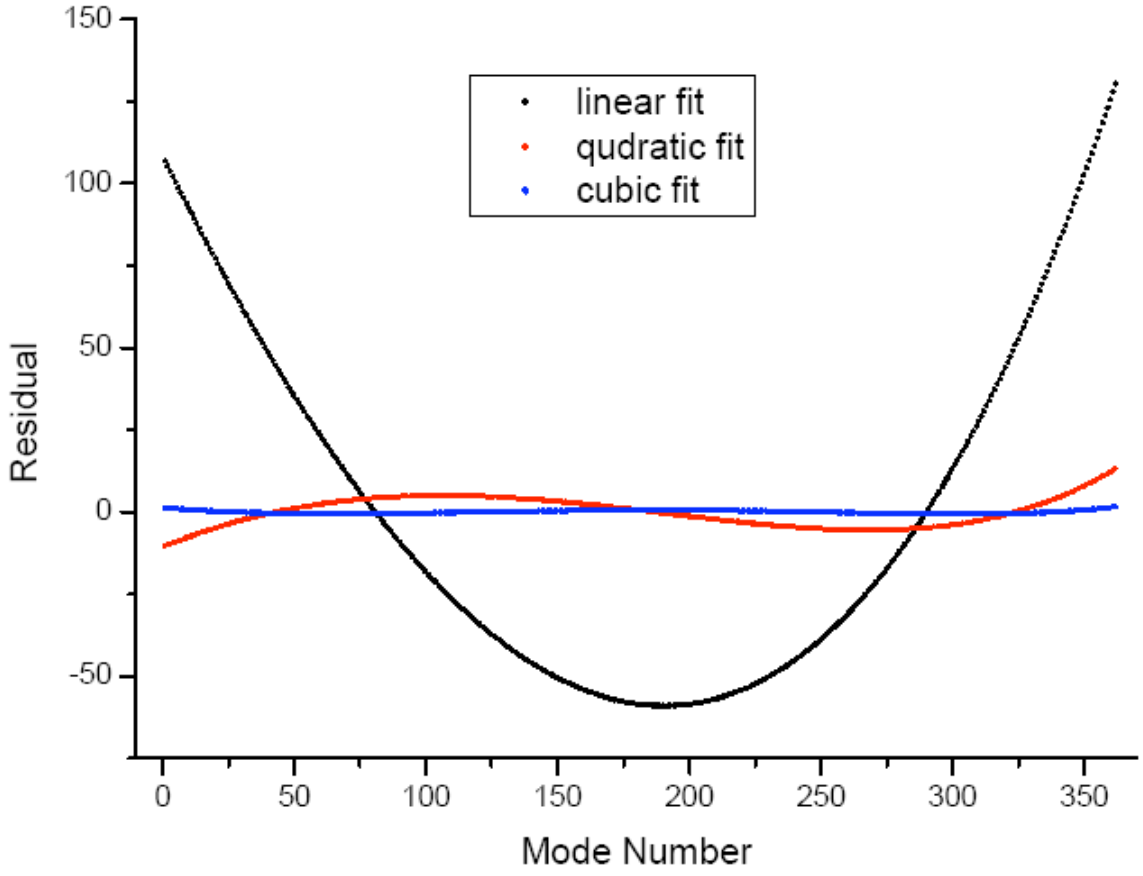
Residuals after fit

1 pixel is approx. 2 GHz



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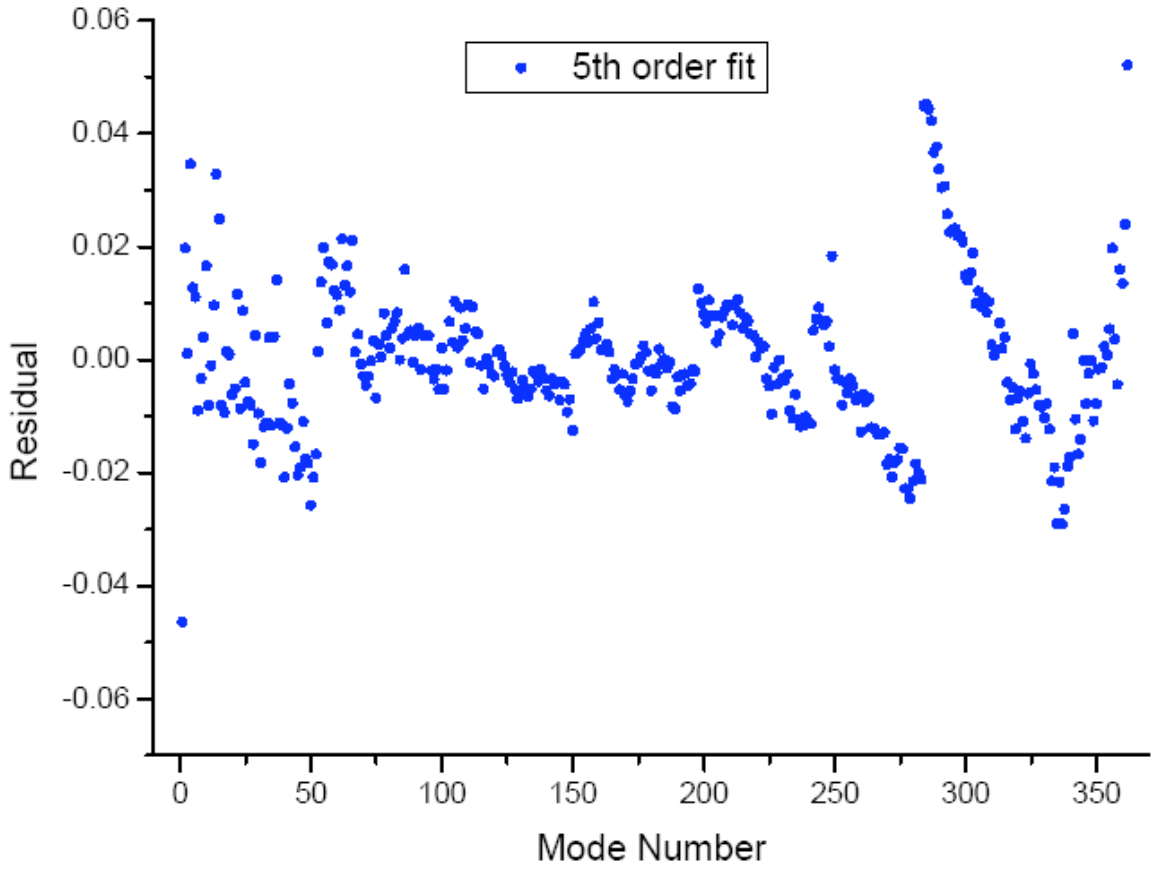
Residuals



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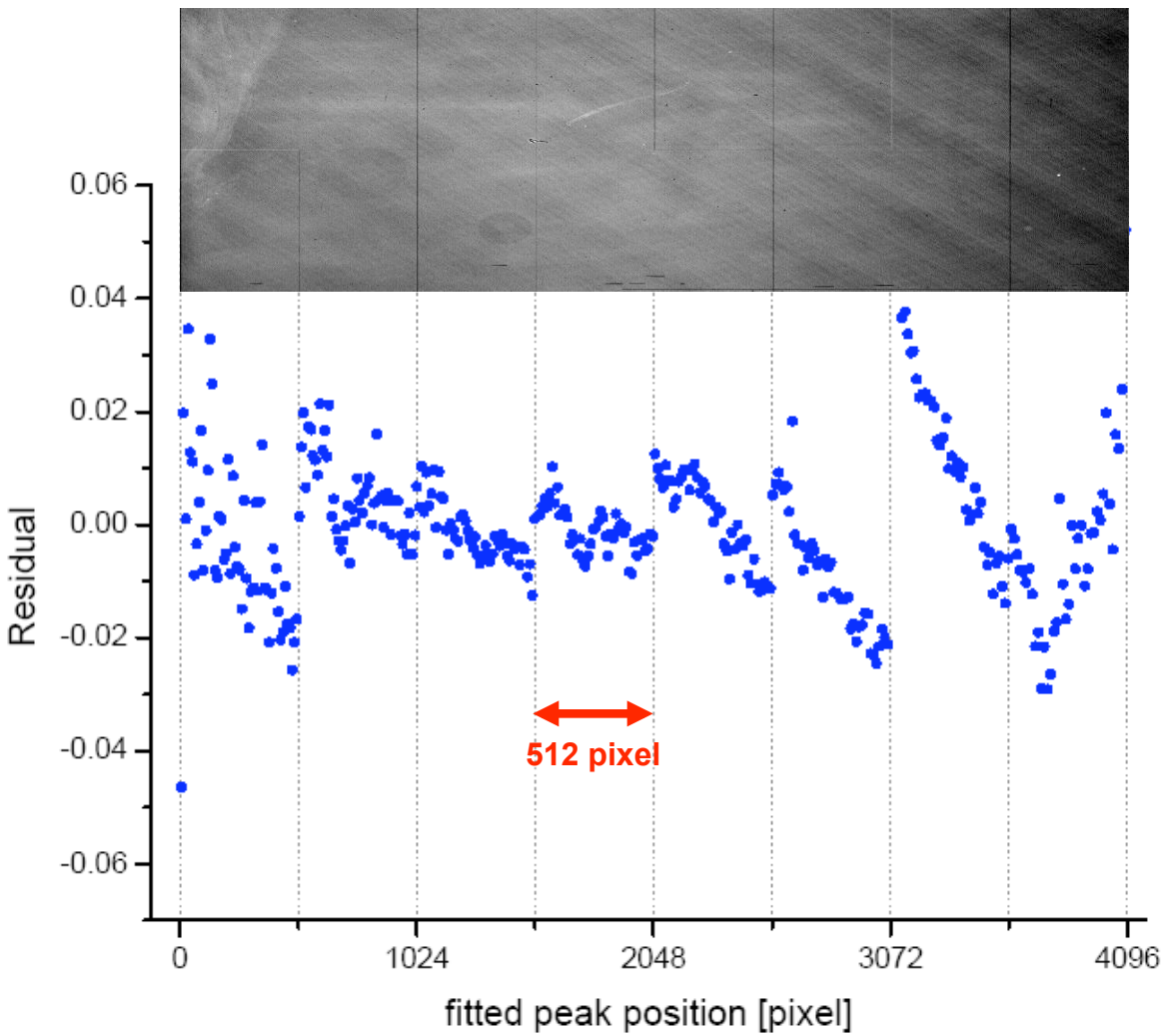
Residuals



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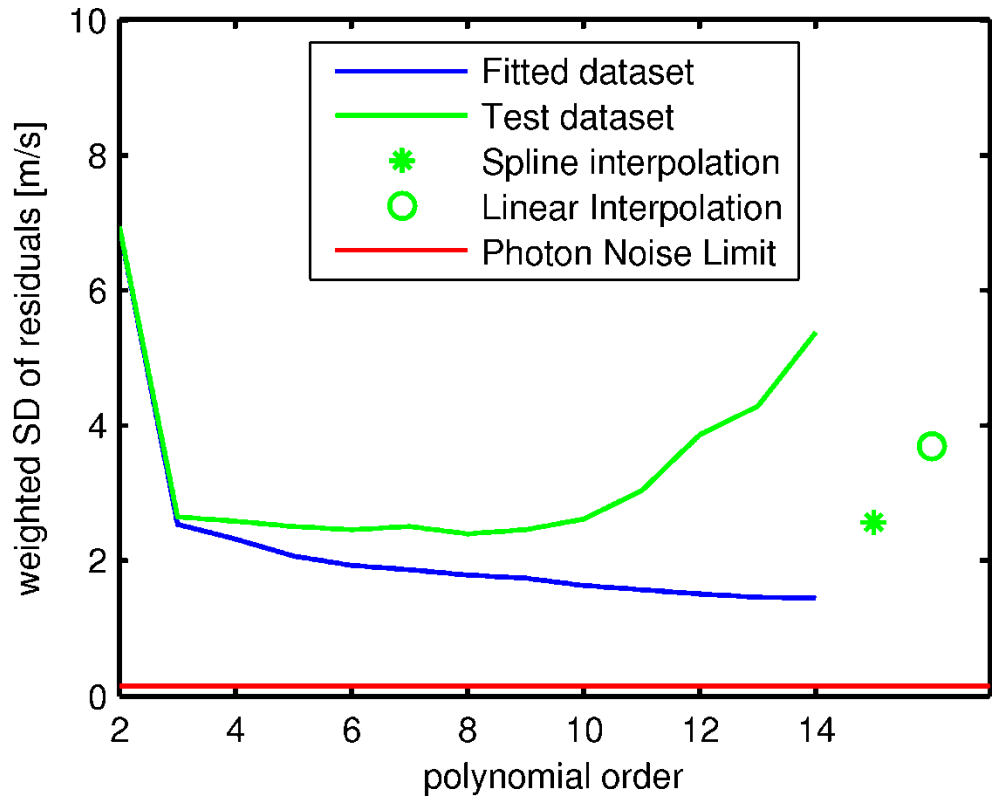
The best Model?

Separate the data in two sets

Fit on every second line

Test the performance on the complementary lines

Fit functions:
8 piecewise polynomials



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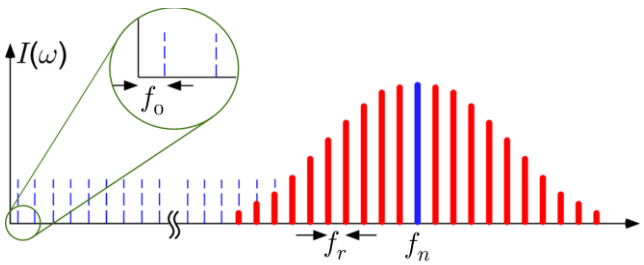
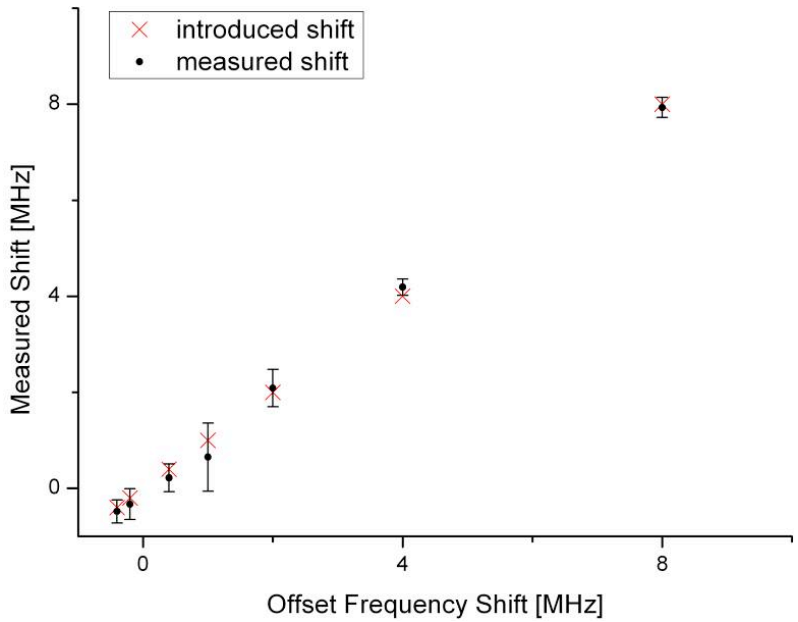
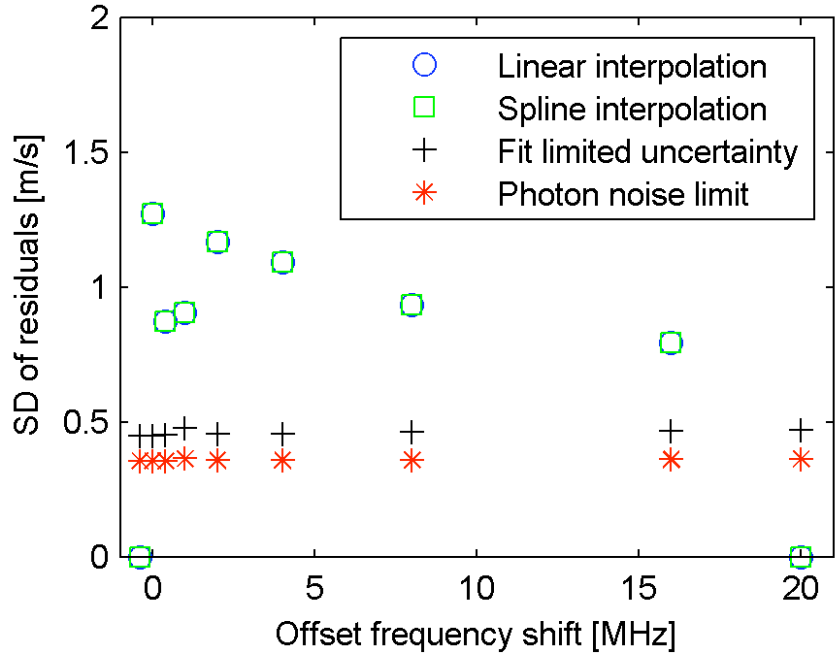
Tuning the Comb



$$f_n = n\, f_{rep} + f_0$$

Degrees of freedom





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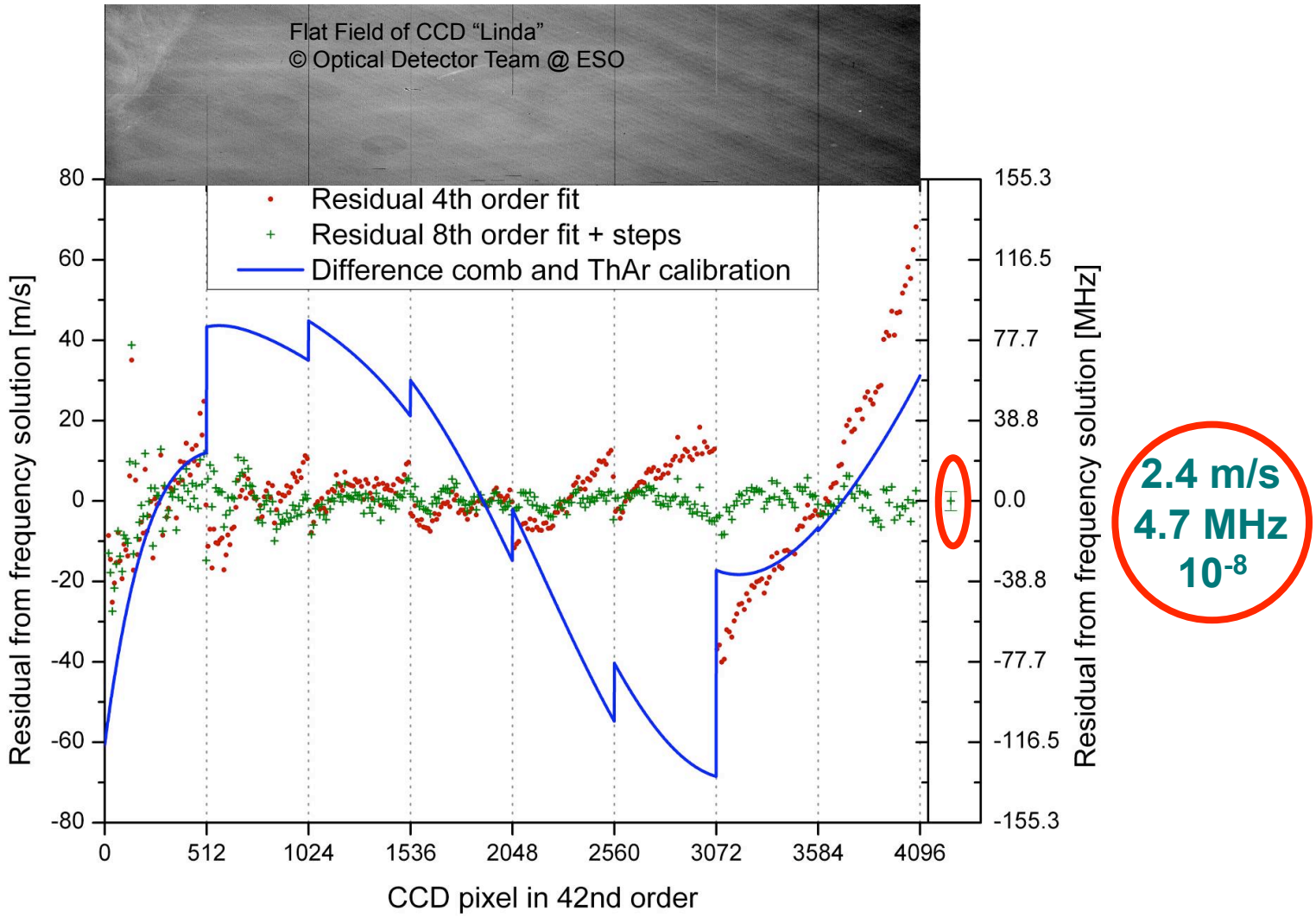
Absolute calibration



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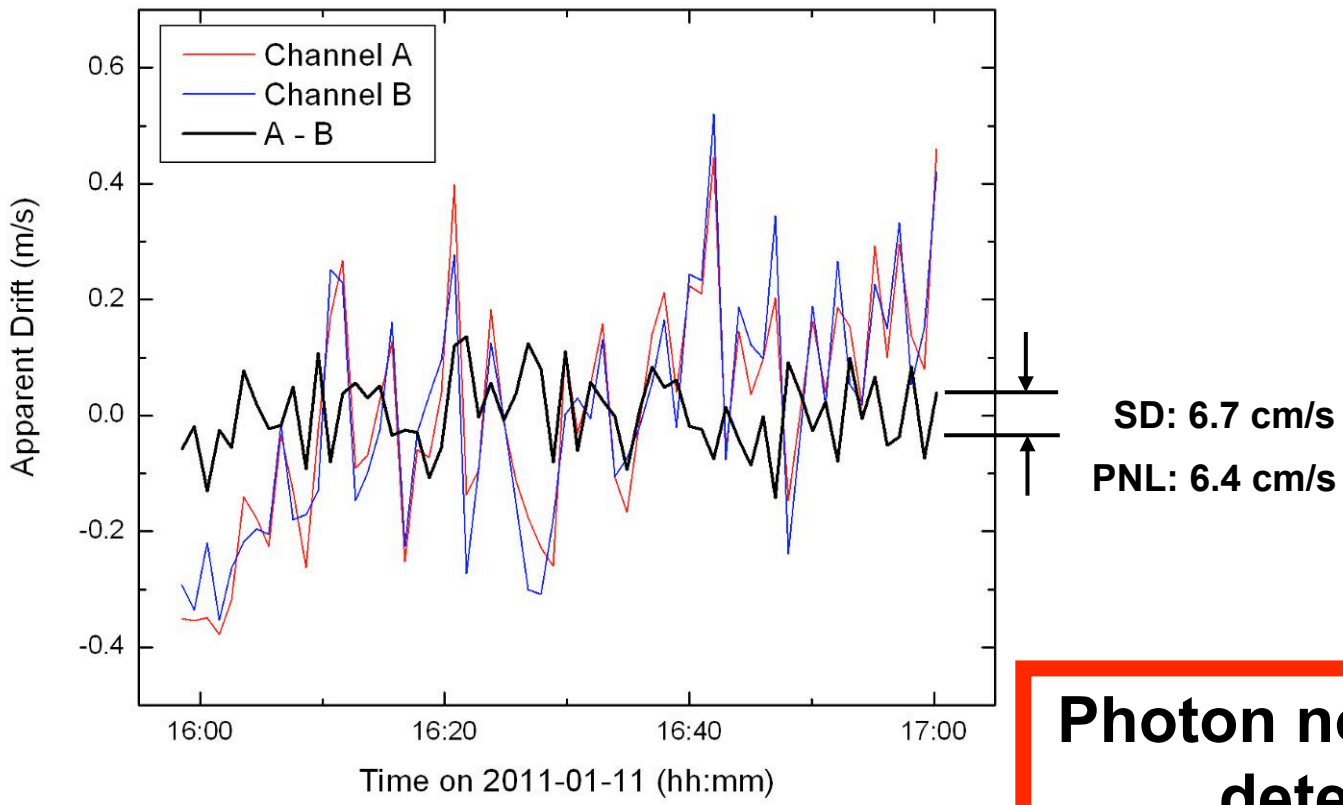
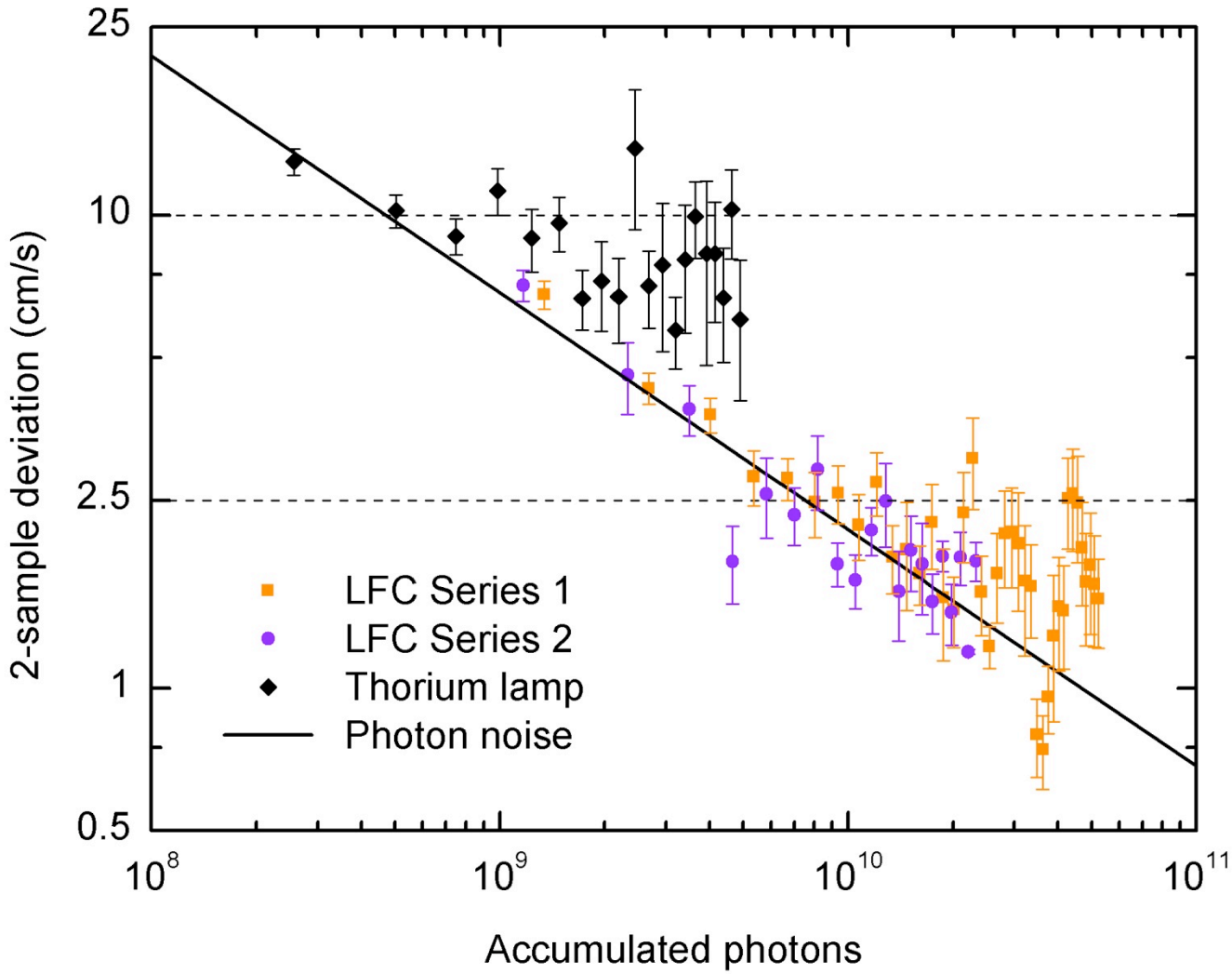
Calibration Repeatability



Photon noise limited detection!

Limit of Repeatability



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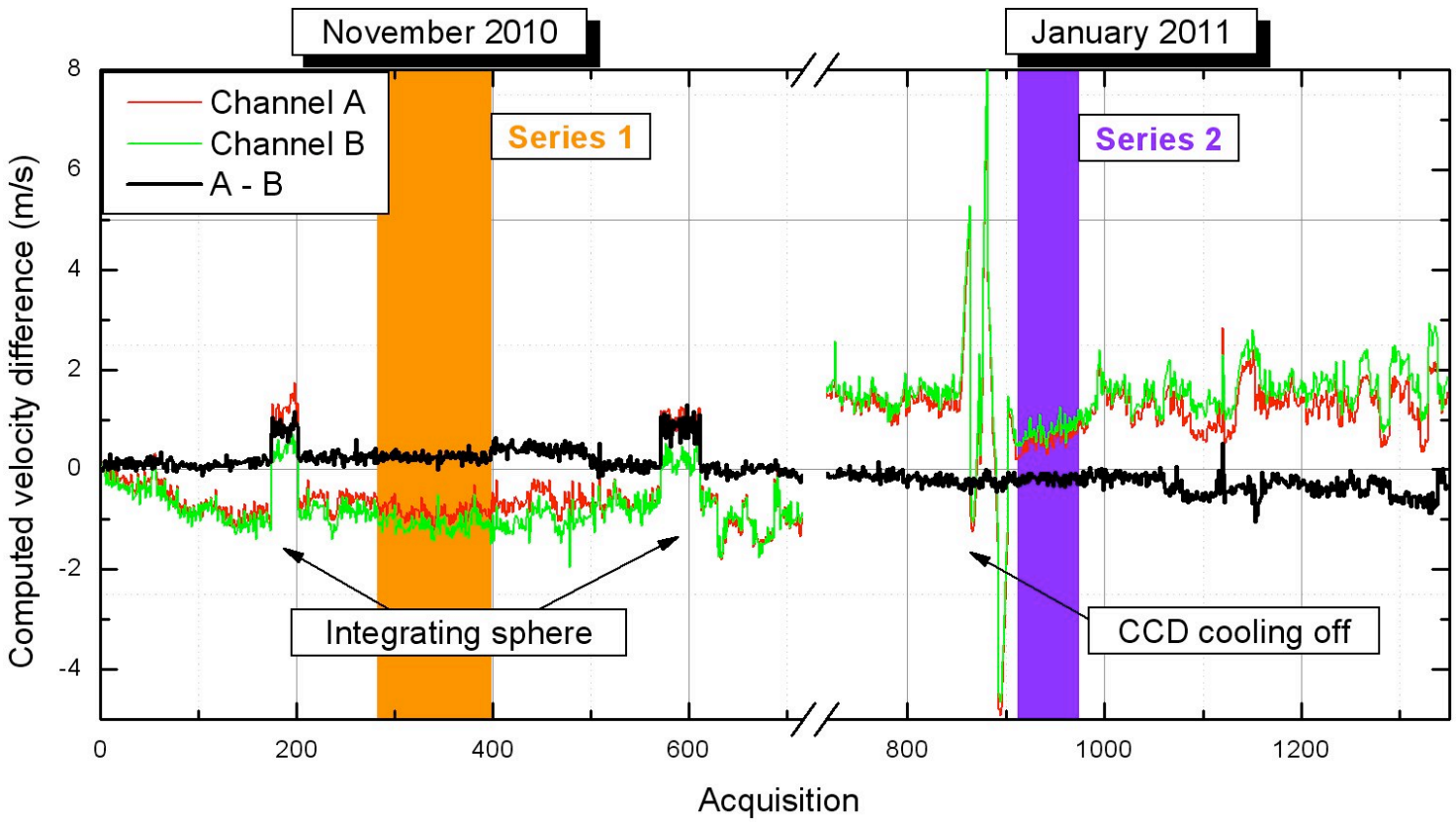
Still some Problems



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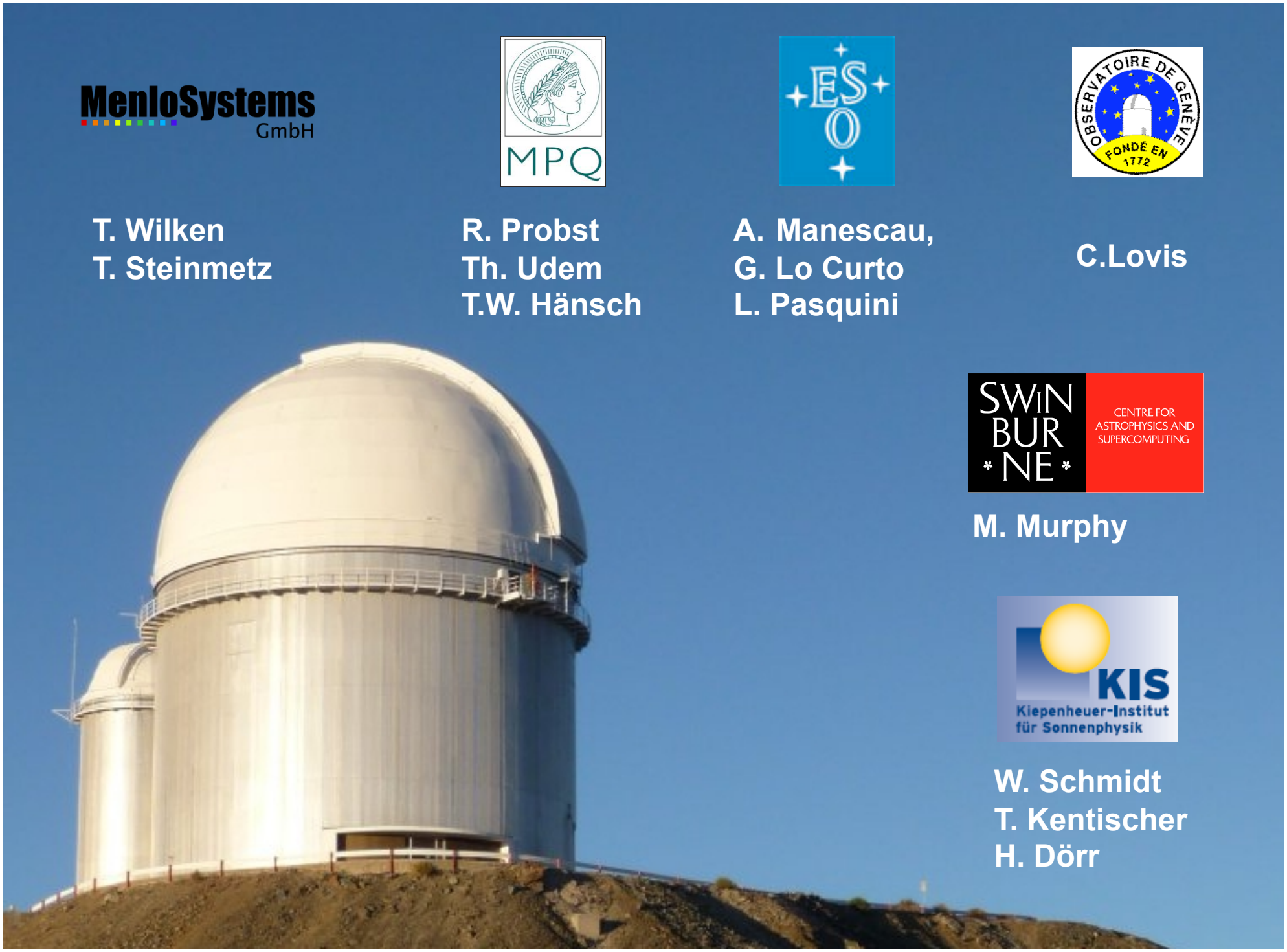
Present hardware status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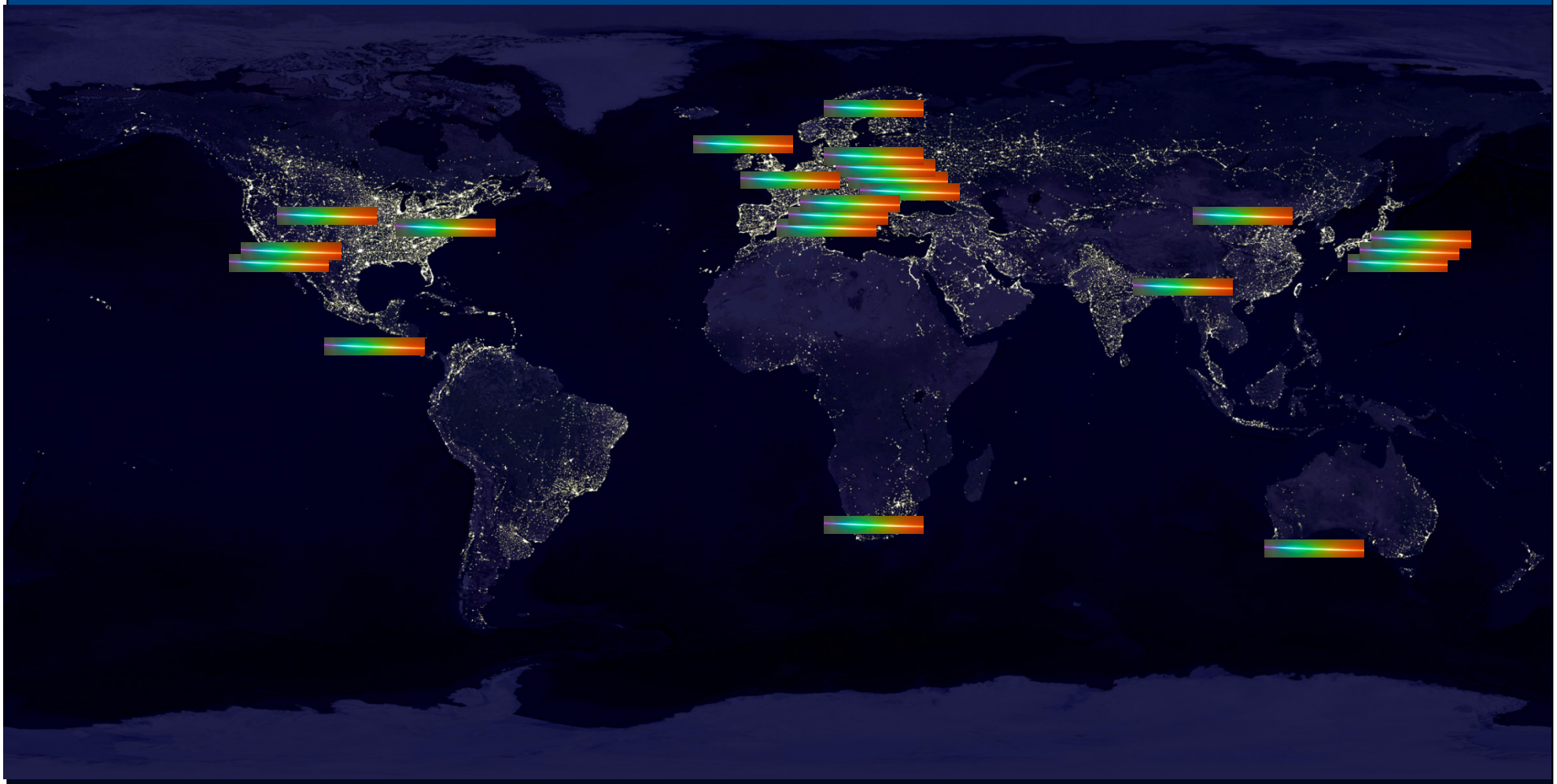
MPQ
ESO
OBSERVATOIRE DE GENÈVE FONDÉ EN 1772
T. Wilken
T. Steinmetz
R. Probst
Th. Udem
T.W. Hänsch
A. Manescau,
G. Lo Curto
L. Pasquini
C.Lovis
SWINBURNE CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING
M. Murphy
KIS Kiepenheuer-Institut für Sonnenphysik
W. Schmidt
T. Kentischer
H. Dörr



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